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Methane number measurements of hydrogen/carbon monoxide mixtures diluted with carbon dioxide for syngas spark ignited internal combustion engine applications

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ABSTRACT

A comprehensive analysis of the autoignition tendency of binary mixtures of hydrogen and carbon monoxide diluted with carbon dioxide is carried out in this paper. Methane Number (MN) measurements of these mixtures were performed by using a method analogous to the standard method for Octane Number (ON) measurement. The experimental MNs ranged from 46.0 to 139.1 according to experimental data. These results are compared with the MNs calculated by programs released for natural gas MN estimations. A comparative analysis concluded that these programs are not suitable to calculate MN of syngas. A method to isolate the effect of carbon dioxide on the autoignition tendency of binary mixtures of hydrogen and carbon monoxide is proposed. Results reveal that increments of carbon dioxide concentration in the mixtures, exponentially increase the MN of the mixtures. At low carbon dioxide concentration, the MN of the ternary mixtures can be approximated by the MN of their equivalent binary mixtures of hydrogen and carbon monoxide. Based on this observation, the MNs of coal gases reported in the literature are estimated.

1. Introduction

Environmental effects caused by the use of conventional fuels and the uncertainty of the future of energy supply have been a concern in recent years. The use of alternative gaseous fuels extracted from a variety of feedstocks such as coal, biomass and waste products is a possible solution; however, for Internal Combustion Engine (ICE) applications their use is limited by their knock tendency promoted by the high concentration of hydrogen and carbon monoxide. The knock resistance of gaseous fuels is determined through the Methane Number (MN), a metric similar to the concept of Octane Number (ON) for liquid fuels. This concept was introduced by Leiker et al. [1] who used the standard ASTM ON determination method as a reference to measure MN of natural gas. Callahan et al. [2,3] used this methodology to measure MN of blends of methane, ethane, propane, butane, pentane, and carbon dioxide. These experimental data were used to develop free [4–6] and licensed [7–9] MN programs to estimate the MN of natural gas as a function of its composition. The programs MN estimations deviate considerably with respect to experimental data when producer gas or syngas are considered as fuels [10,11].These deviations are mainly caused by the high concentrations of carbon monoxide, carbon dioxide and hydrogen in the fuels. To overcome this issue, experimental measurements must be carried out to examine the effect of these species on MN. The MN measurement of gaseous fuels different from natural gas was addressed by Malensek [12], who measured the MN of eight fuels with typical compositions of coal, wood, digester, landfill and, reformed natural gas. Later, Arunachalam [10] and Wise et al. [13] measured MN of producer gases with different compositions to determine their knock characteristics. Although some progress has been achieved, it is desired to expand the MN database for developing robust MN programs that include fuels with high concentration of carbon monoxide, carbon dioxide and hydrogen. The use of ICE models

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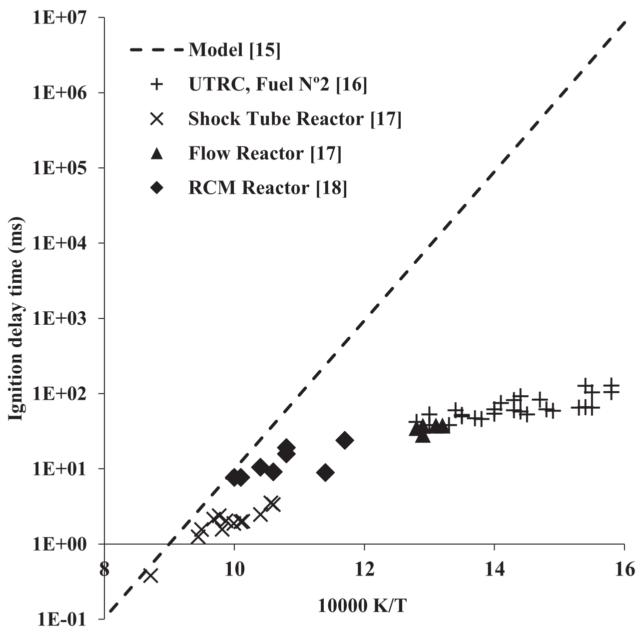

Fig. 1. Ignition delay times of hydrogen, carbon monoxide and carbon dioxide mixtures as a function of temperature. All computations were done through Chemkin Pro package V18.1. Conditions: 38.6% H_2+51.1% CO + 10.3% CO_2 + Air, $\phi = 0.5$, $11.9 < P < 23$ atm, (UTRC,Fuel N° 2 [16]); $16.5 < P < 28.9$ atm, (Shock tube reactor [17]); 50.0% CO + 50.0 % H_2 + Air, $0.33 < \phi < 0.6$, $5.0 < P < 5.3$ atm, (Flow reactor, [17]); $(4.7 < \%H_2 < 24) + (2.9 < \%CO < 16) + (18 < \%O_2 < 20) + (17.6 < \%N_2 < 63.2)$, $0.2 < \phi < 1$, $11 < P < 19.5$ atm, (Rapid compression machine [18]).

coupled with detailed chemical kinetic mechanisms is a new alternative to estimate MN of gaseous fuels [11,14]. However, this technique is limited by the lack of accuracy of the mechanisms used. The lack of accuracy can be evidenced through the estimations of low-temperature ignition delay time, a combustion parameter that describes the knock tendency of fuels. Fig. 1 illustrates the estimation of ignition delay times of ternary mixtures of hydrogen-carbon monoxide–carbon dioxide as a function of temperature by using the detailed chemical kinetic mechanism developed by Li et al. [15]. It is observed that the lack of accuracy of the mechanism increases as temperature decreases. This lack of accuracy evidences the difficulties for predicting autoignition and thus MN of gaseous fuels since MN measurement is based on the autoignition of the test and reference fuels. The experimental data plotted in Fig. 1 can be used to optimize chemical kinetic mechanisms for modeling autoignition and therefore engine knock. To determine the knock rating of these mixtures through MN is a step forward to characterize these fuels and improve the computational technique.

In this work, binary mixtures of hydrogen and carbon monoxide diluted with carbon dioxide were tested in order to:

- Measure their MN and to develop an empirical correlation to calculate the MN as a function of the fuel composition
- Evaluate the performance of free and licensed programs to calculate the MN of the ternary mixtures
- Evaluate the influence of the carbon dioxide concentration on the MN of the ternary mixtures and
- To estimate the MN of the coal gases reported in [16].

2. Methane number measurement

2.1. Experimental setup

The Cooperative Fuel Research engine (CFR-F2 model) used in this

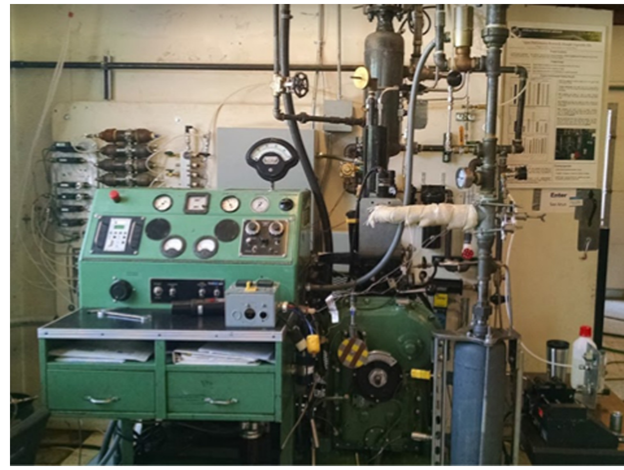

Fig. 2. CFR facility used for MN measurements.

work is shown in Fig. 2. Previously, this engine was employed to measure MN of alternative gaseous fuels [10–12,14]. Originally, this single cylinder, unthrottled, four-stroke, spark ignited engine was designed by the Waukesha Motor Company in 1957 for Motor Octane Number (MON) measurement. It is coupled with a belt to a 5 horsepower AC synchronous motor, which serves to start and load the engine as well as to maintain the engine speed at 900 rpm. The compression ratio (*CR*) can be changed during a test due to the design of the cylinder-piston system, suitable for MN measurements. The modifications made for gaseous fuels testing are focused on the ignition and the intake system. The original ignition system was upgraded to a solid state Altronic CD 200 electronic system, and the engine intake system was upgraded with a pulse width modulated injector (PWM), Clean Air Power Model SP-051 for gaseous fuel metering. The air/fuel ratio control of the engine is based on a feedback control system using either a lambda sensor or air/fuel ratio computed from fuel and air flow measurements. In this work, the latter method was employed due to low heating value fuels were used. The lambda sensor was not suitable for controlling the air/fuel ratio of the tested fuels. This configuration allows running the engine over a wide range of equivalence ratios, depending on the test objectives and fuel composition. Additionally, thermocouples were installed for measuring the intake and exhaust gas temperature. The main characteristics of the engine are shown in Table 1. The gas blending and intake air systems are composed of compressed gas bottles of chemically pure (CP) carbon monoxide, carbon dioxide, hydrogen and, methane. The gas bottles were purchased to prepare the ternary mixtures according to the design of experiment. Regulator valves were installed on each gas bottle for discharging gas into the fuel manifold. Pulse Width Modulated (PMW) injectors were used to meter the fuel blend average flow rate. The mixture flows toward a combination flame arrestor-check valve, mixing later with the intake air. The combustion air was supplied by the building compressed air system, which was filtered and dehumidified. The air/fuel mixture was heated by an electrical heater installed just upstream of the engine intake port.

Intake air/fuel mixture temperature was set at 313 K which was

Table 1
Characteristic of the CFR engine used in this work.

Compression ratio	AdjusTable 4:1 to 18:1
Cylinder bore	8.255 cm
Stroke	11.43 cm
Displacement volume	611.73 cm^3
Piston	Cast iron, flat top
Ignition timing (deg bTDC)	Adjustable from 12 to 30
Connecting rod length	25.4 cm

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