ANALYSIS OF GASEOUS FUEL BLENDS AND MIXTURES USING INEXPENSIVE „GARAGE" GAS ANALYZERS

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Abstract

Projected increases in the cost of conventional fossil energy sources and greenhouse gas emissions caps are among the key drivers for the utilization of various gaseous fuels prepared from biomass in internal combustion engines, primarily in cogeneration units. Due to the low energy content and other poor qualities of many such fuels, they are often intended to be co-fired with diesel fuel, or used in blends with natural gas or other gaseous fuels. Variations in the composition of the biogas, limited capabilities of gas mixing and metering devices, and other factors create challenges in determining the intake charge composition, so that optimal mixture of air and multiple fuels can be maintained. In this study, an experimental device for mixing of two gaseous fuels was tested, with various gases, on a bus engine modified to run on experimental gaseous fuel blends. To evaluate the performance of the mixing device, the composition of the mixture of two fuel gases was continuously analyzed by an inexpensive NDIR „garage-grade" exhaust gas analyzer. The focus of this paper is on the adaptation of the analyzer for this purpose, including calibration and linearization techniques, its verification, and performance. Preliminary results show that this analyzer, commonly used for automobile inspection and maintenance purposes, can serve, albeit with precautions and limitations, as a relatively simple tool for field measurements of the composition of a fuel gas mixture, both raw and mixed with air.

Keywords: Internal combustion engines, gaseous fuel mixtures, biogas, co-generation units, NDIR analyzer, gas mixture analysis

1. Introduction

With fossil fuels becoming more scarce and increasingly more expensive, and with reducing greenhouse gas emissions resulting from their combustion being one of the highest priorities of today's civilized world, people are turning to renewable energy resources. Alcohols, ethers and other volatile compounds are finding their way into petrol engines, while vegetable oils and their derivatives, of which methylester of rapeseed oil is the most popular in Europe, are becoming popular fuels for diesel engines; electricity made from solar and wind energy is trickling into the energy grid; and solar energy and biomass from various sources is utilized for low-grade process and comfort heat. Diverse flammable gases, obtained from digestion of organic materials in municipal waste, sewage, manure, and various forms of biomass, collectively referred to as biogas, form a category on their own. While they are used primarily for heat, they can also be burned in internal combustion engines, which are known for their high efficiency, low cost of operation and reliability, and are likely to remain one of the prime movers of the world. When benefits exceed the costs associated with compact, high-pressure on-board storage of the fuel, biogas can be utilized to power motorized transport and mobile machinery. It appears that one of the most feasible applications of biogas-powered engines is in co-generation units in local or regional power grids, where their ability to quickly vary the power output will be used to stabilize the power grid increasingly laden with energy inputs from intermittent and unpredictable sources such as solar or wind.

As neat biogas is of varying and often relatively low energy content, and biogas represents a small fraction of natural gas usage, it is often blended or co-fired with natural gas. Other mixtures of gaseous fuels, such as hydrogen-natural gas, are also becoming popular target of experimental investigations. Variations in mixture composition, its introduction into the engine via mixing device or manifold or direct fuel injection, formation of lean or stechiometric homogeneous and heterogeneous mixtures, their ignition via compression or various types and shapes of ignition devices delivering varying amounts of energy at various times, degree of internal and external exhaust gas recirculation, different exhaust gas aftertreatment strategies, and other parameters offer nearly an endless pool of options, none of which is, however, optimal for all circumstances given the often contradictory requirements such as high power output, high reliability, low fuel consumption rate and low emissions: For a given engine, one blend of fuels might be optimal for low load operation, while another blend might be more suitable for operation at full load.

In stationary engines, where multiple fuels can be stored on site, a new approach of on-demand blending of fuels can be utilized. For example, an engine might be normally used at fraction of its power load to burn low-grade biogas, the energy content of which would be enhanced by natural gas during peak load operation. It could be that notably in small local power grids, large fluctuations in demanded energy output can be facilitated with the aid of dynamic, on-the-fly blending of fuels. Development, testing and, in many cases, operation of such engines, power generation units, and fuel mixing devices, will require suitable analytical equipment to determine at least a basic composition of the resultant mixture. Such information can be used not only for researchers to know what fuel was actually being combusted, but also for automatic control of the mixing device and of the engine.

The principal components of biogas can be (not all gases are present in all types of biogas) methane, hydrogen, carbon monoxide, carbon dioxide, nitrogen, oxygen, water vapor, and various other gases. Although these other gases can be toxic, corrosive, or undesirable from other reasons, in terms of combustion properties, they occur in small and relatively negligible concentrations. Of the gases of interest, methane, carbon dioxide, water vapor, and many other trace gases can be measured by a suitable FTIR spectrometer, with a response of seconds to tens of seconds, or with a more simple and compact NDIR spectrometer, which can be, however, prone to interference from other gases. Methane and other organic gases can be also measured, after a suitable dilution, by a flame ionization detector. Direct measurement of concentrations of hydrogen is difficult, and is practically limited to a mass spectrometer, although other methods are also investigated. Indirect measurements via conductivity, heat capacity, or density of the gas, are also possible, but these become less reliable for mixtures of multiple gases.

The goal of the efforts described here was to develop a simple, practical, on-line method of determining the content of methane in gaseous fuel mixtures. The need for this method arose while working on a project aimed at evaluating a novel gaseous fuels mixing device and on a project involving basic research of combustion of mixtures of gaseous fuels.

This paper reports on dynamic measurements of the concentrations of methane in gas mixtures using an automotive, garage-type NDIR analyzer. Such analyzers are relatively inexpensive, small in size, robust, available in many regions, and have the added capability of measuring carbon monoxide, carbon dioxide and oxygen.

2. Experimental

The experimental work took place at the Engine Laboratory of the Department of Vehicles and Engines at the Technical University of Liberec, on a test stand with a single-cylinder experimental engine, based on a popular six-cylinder, 11.9-liter turbocharged natural gas engine (Liaz/Tedom, Jablonec nad Nisou, Czech Republic). The engine is fed with compressed natural gas and with hydrogen from the on-site storage. The mass fuel consumption rates are measured, for each fuel,

by a Coriolis-type meter (Micromotion, Boulder, Colorado, USA). A unique experimental mixing device, allowing mixing of two gaseous fuels at an arbitrary ratio, was developed and constructed in-house and installed in the bay, with outlet fed into the pressure regulator of the engine. To analyze the mixture composition, a sampling port was installed upstream of the pressure regulator and fitted with an adjustable pressure reduction valve, from which sample was delivered to the analytical instruments.

Two NDIR optical benches commonly used in garage gas analyzers were used for methane concentrations reading using a hydrocarbon channel at 3.35-3.5 μm [1],[2],[3]. Such wavelength range is normally more suited for higher n-alkanes than for methane, which absorbs fairly weakly in this range, and has a higher absorption around 3.3 μm. Weak sensitivity of the instrument to methane allows, however, for measurements of concentrations up to 100% with the standard optical cell used for measurement of hydrocarbons in the tens to thousands of ppm range.

The NDIR benches were stripped of the entire sample handling system and other auxiliary parts, and operated using a manufacturer-supplied protocol in a very basic mode, without automated functions, warnings, or calibration maps. The sample flow rate was controlled at one liter per minute for each bench. Hydrogen concentrations were also measured by a mass spectrometer (H-Sense, V&F Analyse- und Messtechnik, Austria).

Several sets of measurements were carried. In the first series of measurements, designed to test the mixing device, the hydrogen supply network was filled with dry nitrogen; measurements were therefore done on nitrogen-natural gas mixtures, which were vented outside of the building. In the second series, measurements were done on hydrogen-natural gas mixtures, which were then combusted in the engine. As both testing of the device and engine tests called for a wide range of mixture compositions, no specific test pattern was set.

Prior to the measurements, the analyzers were calibrated with straight pipeline natural gas and either hydrogen or nitrogen. The analyzers were also fed nine intermediate concentrations created by a 10-point capillary flow gas divider (Horiba). At these concentrations, the actual ratios produced by the gas divider depend on gas viscosity and other factors. Viscosities for hydrogen, methane, natural gas and nitrogen were taken from literature [4-5] and materials posted on the internet [6-8] notably for natural gas, the values varied. Viscosity corrections factors were also taken from another gas divider manual, which, however, cautions that the correction factors are best to be determined experimentally [9].

3. Results

The raw readings of the HC channel from the NDIR analyzers were first normalized to 0-100% range using nitrogen, resp. hydrogen for zero and natural gas for span reference. Two linearization factors were then applied.

The first factor CF1 has a form of an exponent applied to the normalized reading, and stems from the different absorption coefficients of n-hexane or n-propane (αHC), the concentration of which (cHC) is reported, and methane ($\alpha METH$), the concentration of which is desired ($cmeth$). To arrive at the methane concentrations, the relative transmissivity T of the analyzed mixture with respect to the transmissivity of zero gas must be first computed, according to the Beer-Lambert law, as

$$T = \exp(-\alpha_{HC} * c_{HC} * const), \tag{1}$$

and concentration of methane computed from this transmissivity using the relationship

$$T = \exp(-\alpha_{METH} * c_{METH} * const). \tag{2}$$

This factor was determined by applying a 2710 ppm methane in nitrogen calibration gas to the analyzers to be CF1 = 1.29 and 1.25 for the two NDIR analyzers.

The second factor CF2 stems from the viscosity correction of the gas divider, and follows the relationship

$$C_{corrected} = C_{measured} * (CF2) / (1 + (C_{measured} * CF2)). \qquad (3)$$

The second factor CF2 was determined to be 1.41 and 1.45 for the two benches, close to the 1.473 ratio of viscosities of nitrogen (165.7 µPa.s) and methane (112.5 µPa.s). For the mass spectrometer, a CF2 of 0.747, corresponding to the ratio of viscosities of hydrogen (84.0 µPa.s) and methane, was applied. The calibration curves for H-Sense and for NDIR instruments are shown in Fig. 1.

Additional corrections, necessitated by different characteristics of the gases used and by the general non-linearities of the NDIR system, which was used at the edge of its design limits, and of the data acquisition system, were generally relatively very small and are beyond the scope of this paper.
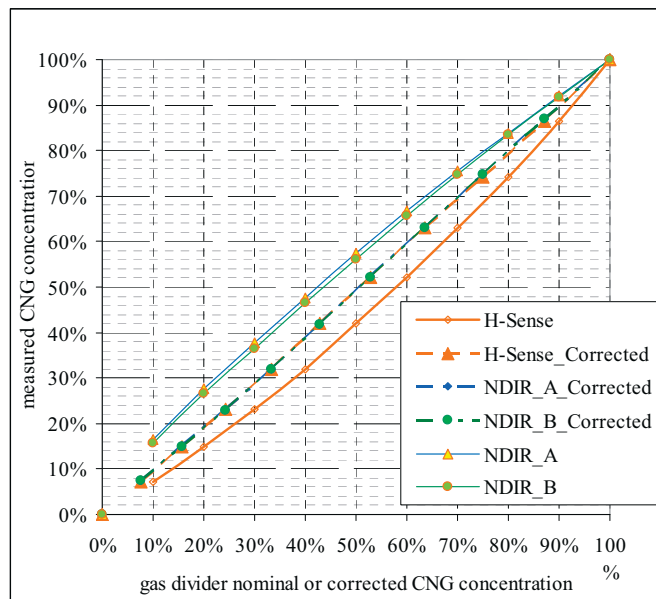

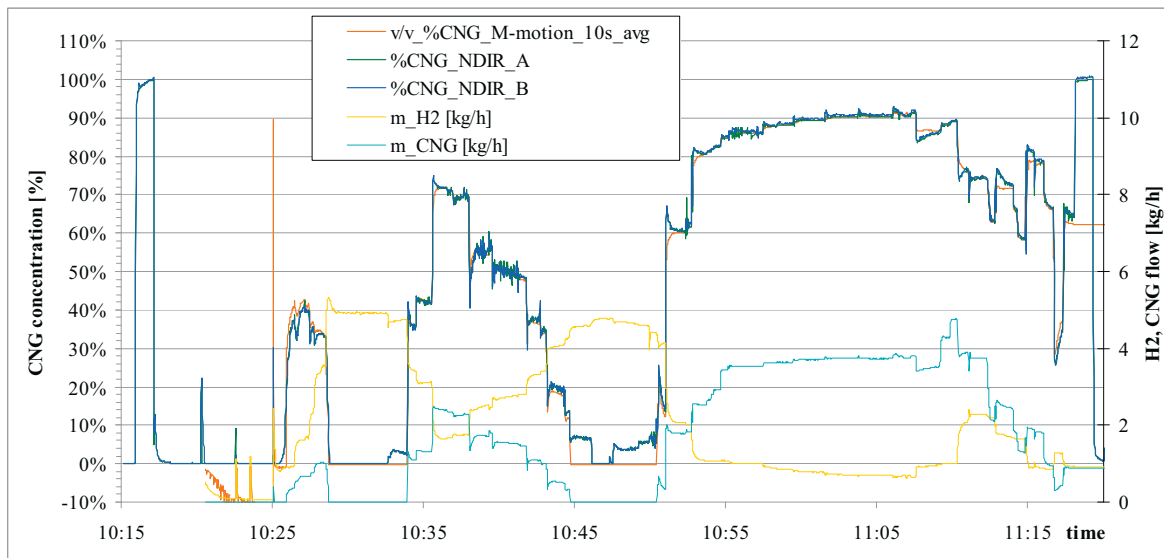*Fig. 1. Multi-point calibration of the instruments using a gas divider*

Fig. 2. Natural gas concentrations measured by NDIR vs. computed from mass flow of gases for nitrogen and natural gas mixtures

The results for nitrogen and natural gas mixtures are shown in Fig. 2, with details of the transients shown in Fig. 3. The results for mixtures of hydrogen and natural gas are shown in Fig. 4, with details of transients in Fig. 5. The traces are shifted in time in order to compensate for different locations and different response times of the instruments.
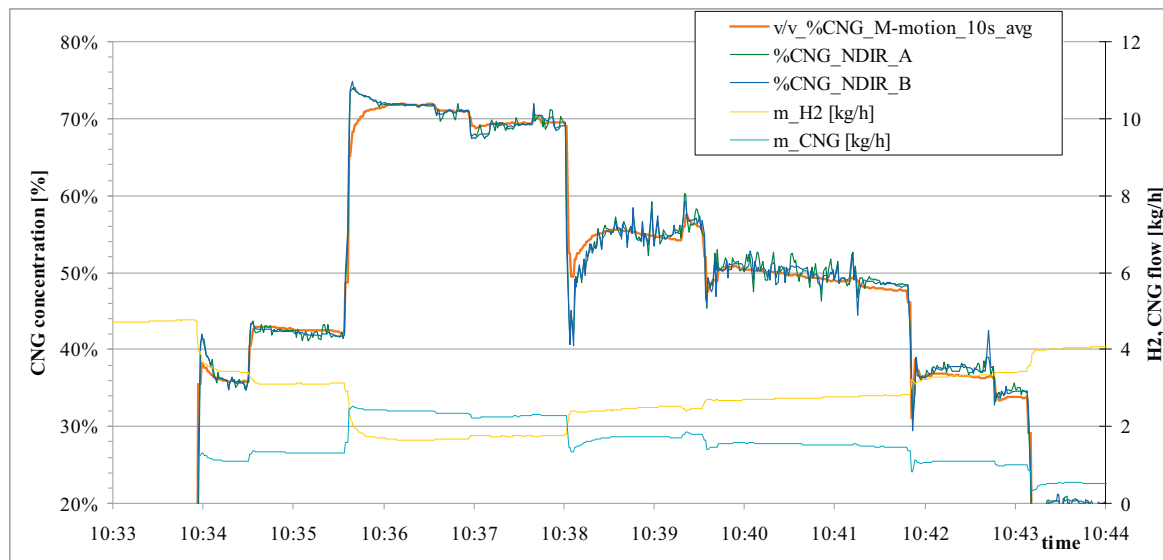

Fig. 3. Natural gas concentrations measured by NDIR vs. computed from mass flow of gases for nitrogen and natural gas mixtures - detail of transient response of the analyzers
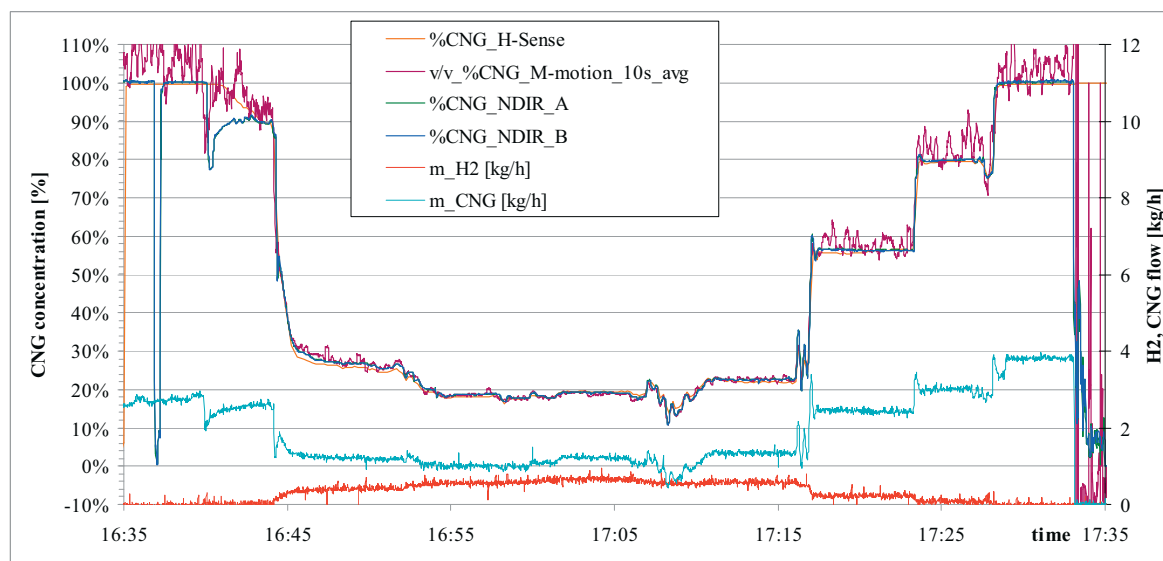

Fig. 4. Natural gas concentrations measured by NDIR and computed from H-Sense mass spectrometer hydrogen concentrations and from mass flow of gases for hydrogen and natural gas mixtures

4. Discussion

The methane concentrations determined from direct measurement by the two NDIR benches, computed from hydrogen concentrations measured by the mass spectrometer, and computed from the ratio of mass flows of natural gas and hydrogen, each measured by a Coriolis-type flow meter, are relatively comparable. Some drift was observed in the mass-spectrometer readings.

Differences are apparent in transients. The mass spectrometer reports data in 11-seconds intervals, and follow a relatively smooth line. The NDIR instruments report data every second, and once the sample reaches the sample cell, the transient response is relatively fast, on the order of two seconds. The transient response of the gas flow meters is generally good.
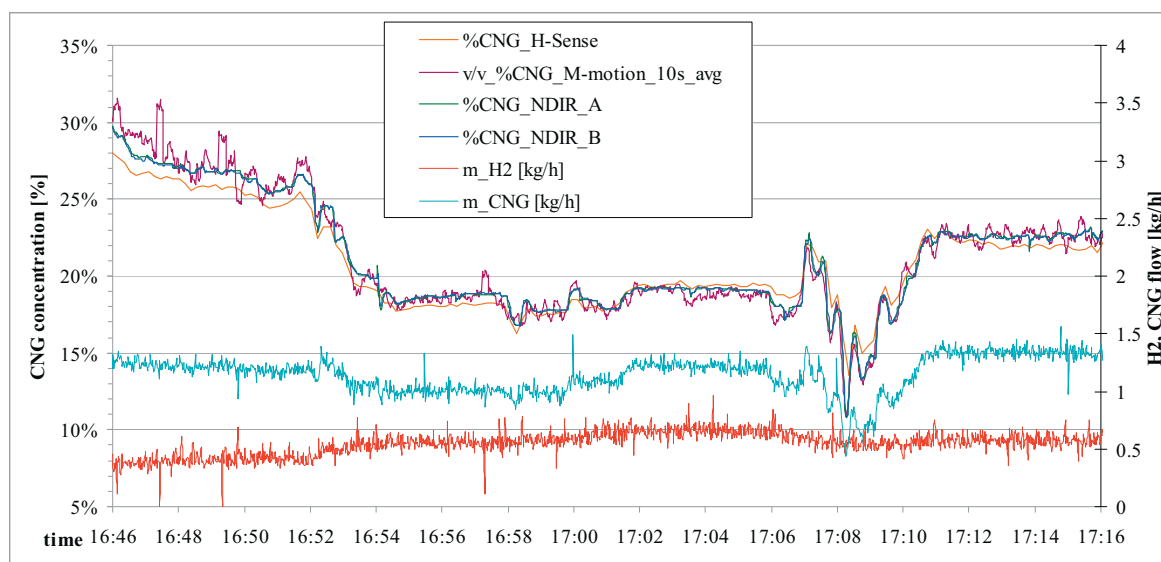
Fig. 5. Natural gas concentrations measured by NDIR and computed from H-Sense mass spectrometer hydrogen concentrations and from mass flow of gases for hydrogen and natural gas mixtures - detail of transient response of the analyzers

Large, step-function changes in concentrations are a result of commanded control of the mixing device. Drifts are a result of transient response and adjustments of the mixing device. Fast transients recorded by the NDIR instruments are generally a function of the mechanical gas metering regulation of the mixing device. Fast transients recorded by the flow meters, located at the central place in the laboratory, are more a function of the operation of 2 MPa reduction valves located upstream of the meters, and do not represent the operation of the flow meter.

It appears that the transients in mixture composition at the engine were best captured by the NDIR instruments, which can be located close to the engine and have a good transient response. This transient capability is important for providing feedback with a reasonable delay for the control of the mixing device, engine and exhaust gas aftertreatment system.

5. Conclusions

In this project, concentrations of natural gas in dynamically prepared mixtures of natural gas and nitrogen and of natural gas and hydrogen were measured with NDIR optical benches, used in common garage-type automotive gas analyzers. The measured concentrations were comparable to concentrations inferred from mass spectrometer and gas flow meter readings. The NDIR instruments provided a good transient response, and overall, they appear to offer a simple, practical, inexpensive, reliable, on-line method of determining the content of methane in gaseous fuel mixtures.

Acknowledgements

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