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Development of a fuel sensor technology for a Variable-blend Natural Gas Vehicle

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ABSTRACT

Natural gas vehicles (NGVs) with the ability to accept a broader range of fuel specifications can play a significant role in increasing Renewable Natural Gas (RNG) utilization in the transportation sector. The Wobbe Index is a critical factor in evaluating the interchangeability between different high methane fuels. This study details the development and testing of a compact, reliable Wobbe Index sensor for use in NGVs.

The concept uses a combination of a thermal conductivity and an infrared sensor together with temperature and pressure measurement. The signals from these sensors are indexed in an algorithm that estimates the Wobbe Index in real time. The sensor was confirmed to operate over a temperature range of −20 °C to 70 °C under pressures of up to ~3600 psi. A multivariate algorithm was developed to estimate the fuel Wobbe Index from the measured temperature, pressure and thermal conductivity data. The accuracy was improved to ±1% using the CH_4 concentration data from the IR sensor additionally.

Compared to the existing methods, this sensor provides a cost-effective, ruggedized solution that can be used to develop a "Variable-blend Natural Gas Vehicle"(VNGV), allowing refueling from a broad range of natural gas sources. This technology has the potential to significantly increase RNG usage for transportation purposes.

1. Introduction

Renewable Natural Gas (RNG) is an important alternative fuel that can contribute to achieving a number of goals set by local and national governments related to conventional fuel replacement and Greenhouse Gas (GHG) emissions reduction in the transportation sector.[1] Natural Gas Vehicles (NGVs) have achieved reasonable market penetration over the past decade. However, significant increase in the number of NGVs running on RNG is needed in order to make an impact on net GHG emissions. Most RNG projects are small to medium scale by nature and comprehensive gas cleanup/upgrading to meet NGV fuel specifications is often not feasible from a project economics perspective. This results in most RNG resources being left undeveloped or wasted, such as in the case of landfill gas flaring. Developing NGVs that are capable of accepting a broader range of RNG fuel properties can help achieve widespread RNG usage for transportation. The typical calorific value of RNG from biogas or landfill gas projects is around 50–60% of equal volume fossil Natural Gas (NG). Table 1 shows the composition of RNG from the various source along with conventional NG.

A critical factor in evaluating the interchangeability between different high methane fuels such as fossil NG, Synthetic Natural Gas (SNG) and RNG is Wobbe Index[2] (the term SNG is used to denote synthetic methane produced from all carbonaceous feedstocks such as coal, biomass, etc., whereas RNG is produced from renewable feedstocks). Wobbe Index is the ratio of the fuel's calorific value to the square root of its specific gravity and is a well-known parameter to evaluate fuel interchangeability. Wobbe Index is used in estimating the energy output in a wide variety of equipment and processes that involve NG combustion since fuels with identical Wobbe Indices will generate similar energy outputs under given conditions.

To enable the usage of typical RNG in NGVs without

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[1] U.S. Department of State, 2014, section 3. U.S. Climate Action Report 2014 (2014 CAR). < http://www.state.gov/e/oes/rls/rpts/car6/index.htm>.

[2] A.H. Kakaee, A. Paykani, M. Ghajar, The influence of fuel composition on the combustion and emission characteristics of natural gas fueled engines, Renew. Sust. Energy Rev., 38 (2014), pp. 64–78.

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Table 1
Characteristics of different high methane fuels[a].

Type of fuel	Biogas	Natural Gas (fossil)
CH_4	50–75%	97% CH_4
CO_2	25–50%	–
N_2	0–10%	0.4%
H_2	0–1%	–
H_2S	0–3%	–
O_2	0–0.5%	–
C_2+	–	2.6%
Wobbe Index (MJ/m^3)	25–45	~50

[a] A. J. Bruijstens et al. "Biogas composition and engine performance, including database and biogas property model" Stockholm: Biogasmax (2008).

comprehensive gas upgrading or with limited upgrading, engine control parameters such as air fuel ratio, and injector pulse width have to be adjusted. This will allow the vehicle to compensate for variation in fuel characteristics.[3] Such a vehicle, designated as a "Variable-blend Natural Gas Vehicle"(VNGV), would run on conventional NG, but could also operate on any arbitrary mixture of NG, RNG or SNG, thus allowing refueling with a wide range of high methane fuels. A key enabling technology required to develop VNGVs is an on-line fuel Wobbe Index sensor that can measure the fuel's Index in real time. The concept of the proposed VNGV with built in fuel Wobbe Index sensor is shown in Fig. 1.

The Wobbe Index sensor is located in the fuel tank or in the fuel line and directly communicates with the Engine Control Unit (ECU). An engine control algorithm will enable the ECU to read the sensor signal and adjust the fuel injector pulse width according to the Wobbe Index. Adjusting the ignition timing based on the CH_4 content (by using a separate methane index) is also recommended by the research team.

Commercially available Wobbe Index measurement techniques typically involve bulky, complex and expensive analyzers. These devices measure the energy content of the fuel through direct combustion (Calorimetry) and separately measure fuel density using optical methods. Past efforts to develop a portable Wobbe Index analyzer[4] have also relied on direct calorific value measurement in a catalytic combustion chamber followed by sample density measurement. Such analyzers cannot be used in a vehicle as envisioned in this article, since it has not only bulky size, slow analysis time and safety concern from calorimetric analysis, but also issue for the reliability in the harsh environment of automotive.

The objective of this study is to design a rugged, cost effective sensor and to interpret the signals using chemo-metric methods. The signals from the sensor will be indexed in an algorithm and the Wobbe Index will be indirectly determined in real time. The target accuracy for the proposed sensor, based on the performance on other automotive sensors (ex., oxygen sensor), is within ±5% of the actual Wobbe Indices. Successful commercialization of this technology will be a major step towards significantly increasing RNG use in transportation sector.

2. Experimental

2.1. Sensing technology selection

The proposed concept requires the measurement of a multiple set of indirect variables to find the relationships between the indirect variables and the Wobbe Index. The higher number of independent variables, which provide different responses to the fuel composition changes, results the better prediction. In addition to the pressure and temperature measurement of the fuel, thermal conductivity and/or point infrared sensors were selected as candidate technologies, since these measurements are proven reliability in the temperature range of −20 °C to 50 °C and pressures of up to 3600 psi, which is the common specification as the automotive application. Table 2 summarizes the characteristics of two sensing technologies.

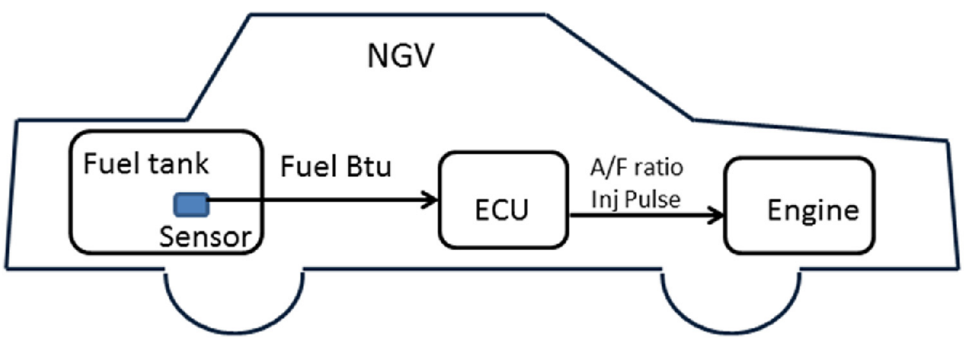

Fig. 1. Proposed VNGV concept.

2.2. Thermal conductivity detectors

The Thermal Conductivity Detector (TCD) measures the thermal conductivities of the gas. This detector contains a sensing element (typically filament or film) that is heated electrically so that it is hotter than the surrounding gas. The temperature difference between the surrounding gas and sensor is directly related to thermal conductivity of the gas.

Since the thermal conductivity of CH_4 is almost twice as high as that of CO_2, it can be used as the major indexing signal that distinguishes RNG from conventional NG. TCDs can operate over a wide range of temperatures and pressures. The operating temperature and pressure range of a typical TCD covers and exceeds the required parameter range.

The major advantages of TCD for the current application as a VNGV sensor are:

- Hot film anemometer, a technology similar to TCD, is widely used as mass air flow sensor in automotive applications, proving

[3] K. Kim, H. Kim, B. Kim, K. Lee, K. Lee, Effect of natural gas composition on the performance of a CNG engine, Oil Gas Sci. Tech., 64(2) (2009), pp. 199–206.
[4] J. Adrianus, T. Hornemann, Method for determining the calorific value of a gas and/or the Wobbe index of a natural gas, US Patent 5807749 A, 1998.