Title

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Journal

Journal of Natural Gas Science and Engineering, 31

ISSN

18755100

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Publication Date

2016-04-01

DOI

10.1016/j.jngse.2016.03.020

Journal of Natural Gas Science and Engineering 31 (2016) 149–155

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

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

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ARTICLE INFO

Article history:
Received 20 October 2015
Received in revised form
19 January 2016
Accepted 6 March 2016
Available online 8 March 2016

Keywords:
NGV
VNGV
Wobbe index sensor
Renewable natural gas
RNG

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.

http://dx.doi.org/10.1016/j.jngse.2016.03.020
1875-5100/

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.

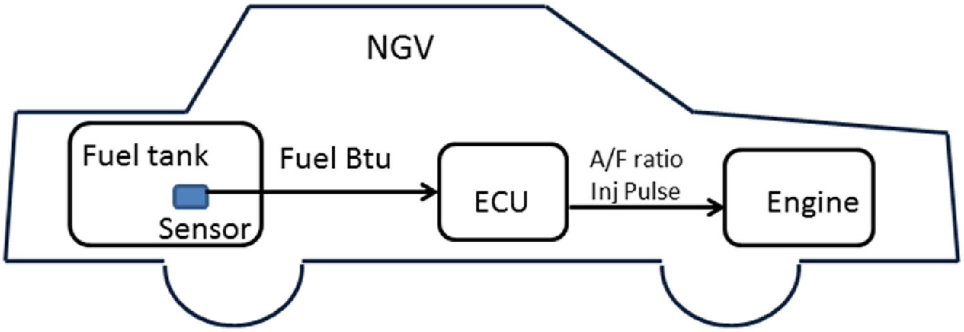

Fig. 1. Proposed VNGV concept.

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.

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

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[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.

Table 2
Characteristics of candidate sensors.

Gas sensor type	Benefits	Issues
Thermal Conductivity	Can measures concentrations of gas mixtures even in the absence of oxygen.	High gas concentration only. Limited range of gases. Fragile (wire type).
Point Infrared	Selective measurement to the certain species. Can be used in inert atmospheres. Can be located inside the fuel tank/fuel line	Low sensitivity. Higher cost than Thermal Conductivity. Sensor with gas cell cannot be used because of pressure rating

the cost-effectiveness, ruggedness, and reliability of the TCD technology.

- Routine calibration is not required and the sensor is virtually maintenance free.
- Can operate in continuous presence of gases in pressurized environments, and covers wide temperature ranges.
- Universal response to the all gas species. This characteristic, when combined with a specific detector such as the infrared sensor, provides an excellent chemo-metric analysis option.

The concerns are:

- Surface oxidation due to residual oxidative impurities such as trace oxygen in the fuel mix. For this reason, tungsten-rhenium was chosen as the sensing material, since it provides a chemically passivated layer on the sensing element.

The rugged thick film type TCD sensor used here was developed as part of a previous study.[5] The technology was intended to provide a cost effective hydrogen sensor option for hydrogen fueled vehicles and also for hydrogen and synthesis gas sensors to be used in chemical conversion processes.[6] This sensor uses tungsten-rhenium material on a thick film ceramic substrate, has high shock resistance, and can function under extremely harsh conditions for extended periods. A photo of the TCD sensor used in this study is shown in Fig. 2. The schematic diagram of the TCD sensor and the sensor housing used to conduct the experiments is given in Fig. 4(see Figs. 3 and 5).

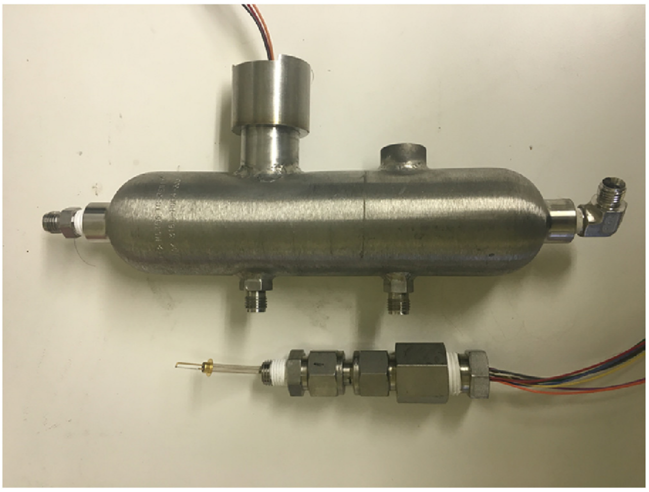

Fig. 2. Prototype TCD sensor (Bottom) and sensor housing (Top).

2.3. Infrared detectors

Infrared (IR) absorption technology based gas analysis has been used successfully for decades. Similar to TCDs, there is no chemical reaction between the gas and the sensor element in IR sensors. They are less susceptible to long-term drift and unlike chemical sensors, are resistant to contamination. Because of these properties, IR absorption sensors can operate over a wide range of temperatures as long as the sensor material is chemically and physically stable throughout the operating temperature range. The typical operating temperature range of −20 °C to 70 °C meets target temperature range required for the current application.

Infrared gas detection is based upon the ability of some gases to absorb IR radiation. Most hydrocarbons, including methane, absorb IR radiation at approximately 3.4 μm in wavelength whereas H_2O and CO_2 are relatively transparent in this region. Therefore, a dedicated configuration operating at this wavelength can be used to detect CH_4.

The major advantages of IR gas detectors for the current application are:

Fig. 3. Infrared gas sensor (Dynament Ltd).

- Immunity to contamination and poisoning.
- Routine calibration is not required and the sensor is virtually maintenance free.
- Ability to operate in the absence of oxygen or air.
- Can operate in continuous presence of gases in pressurized environments.

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[5] J. W. Heffel, P. B. Scott, C. S. Park " Variable Mixtures of Gaseous Fuels Sensor". U.S. Patent No. 6,612,269, Date Issued: September 2003.

[6] Park C, Hackett C, Norbeck J "High Temperature and Pressure Sensor" US Patent Application Publication US 2007/0131567 A1, 2006.

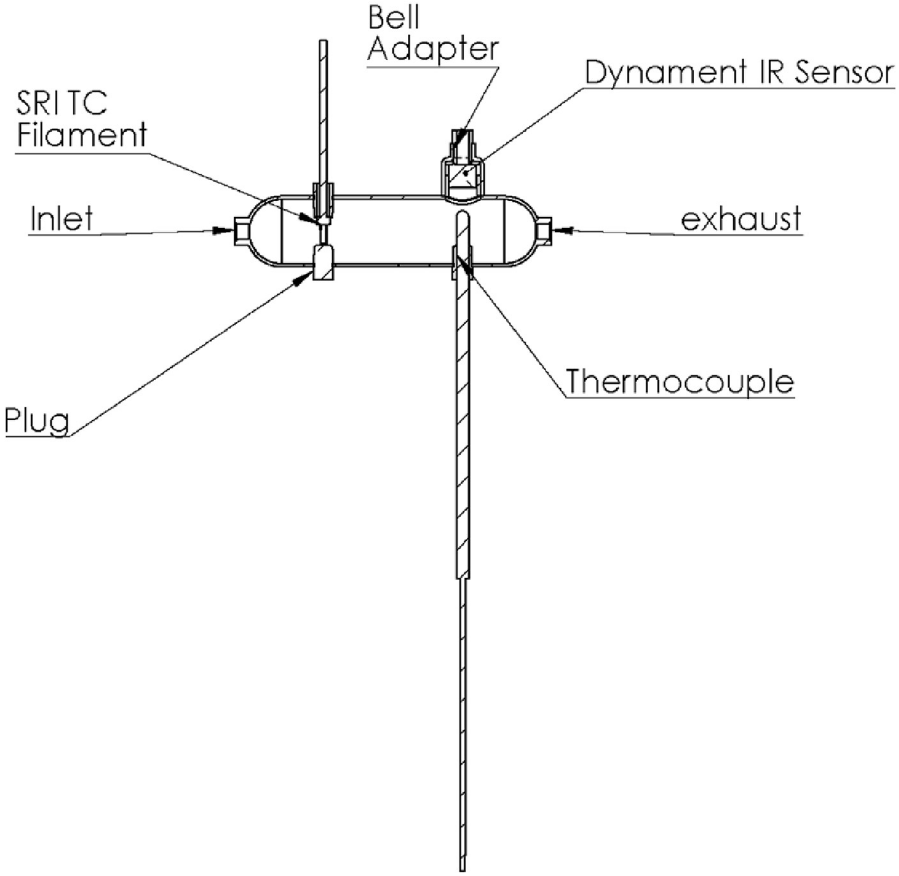

Fig. 4. Engineering drawing of the sensor housing.

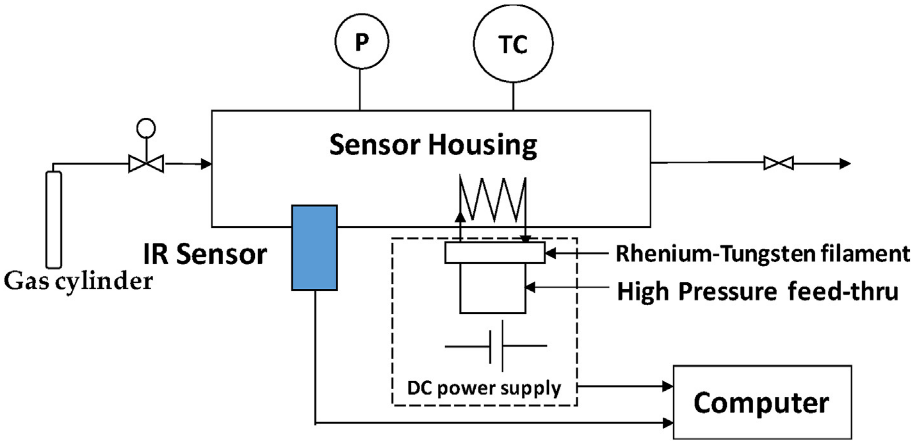

Fig. 5. Schematic diagram of the experimental setup.

- Can be calibrated to response to specific species such as CH_4. This characteristics, when combined with a non-specific detector such as TCD, provides an excellent chemo-metric analysis option.

The concerns are:

- High initial per point cost. IR sensors have in the past been more expensive than other types of sensors, but their price is rapidly decreasing.

Commercially available point type infrared gas sensor from the Dynament Ltd, UK, was selected for this study. The maximum operating pressure of an IR absorption sensor is determined by the sealing or encapsulating techniques used to integrate the sensor to the fuel tank or fuel line. The pressure rating of the infrared window of the sensor element does not influence the maximum operating pressure since the inside of the window is pressurized by the same environment as the outside during operation. In this study, the sensors are located inside the fuel tank, and sealing was performed by blazing followed by thermal compression with high pressure electrical feed-thru. This type of sealing can easily withstand the proposed maximum operating pressure of 3600 psi.

Table 3
Specification of sensors and components used in this study.

Part name	Part number	Vendor	Specifications
Double-ended cylinder	316L-HDF4-300	Swagelok	316L SS double-ended DOT-compliant sample cylinder, 1/4 in. FNPT, 300 cm3, 4000 psig.
Thermal conductivity sensor	N/A	In-house (by Bourns Inc.)	TCD, tungsten-rhenium film and filament (copper seal) on alumina substrate
Premier dual gas IR sensor for HCs and CO_2	MSH–DP/HC/CO2/P	Dynament Ltd.	Methane from 0 to 100% volume with 0.1% volume resolution, 0–2% volume propane, 0–5% CO_2 with 0.01% resolution

2.4. Sensor installation

A sensor testing setup, including a manifold, was developed with a miniature stainless steel gas tank. The entire setup was located within a temperature controlled chamber. Characteristics of the components used in this setup are summarized in Table 3. Engineering drawing is provided in Fig. 4.

2.5. Sensor signal interpretation to Wobbe Index

Parameters including fuel temperature, fuel pressure, TCD sensor output and IR sensor output were measured during testing. For the Thermal conductivity value, resistance of the TCD sensor at varying current that flows to the sensor was measured using a 4-probe digital ohm meter with constant current source (HIOKI PS100). The resistance of the TCD at zero current was measured and used to calculate the temperature of the gas since the resistance of the filament is directly proportional to the temperature of the surrounding gas under given conditions.

The Wobbe Indices of four different gas mixtures were measured during the experiments:

1. Industrial grade methane which has a purity of 99.99%.
2. A mixture of 95% CH_4, 4% ethane and 1% CO_2, which represents fossil NG.
3. A mixture of 60% CH_4, 39% CO_2, and 1% N_2, which represents RNG from household waste.
4. A mixture of 80% CH_4, 18% CO_2, 1% O_2, 1% N_2, which represents a median between the NG and RNG.

These gas mixtures were obtained from RNG composition databases reported in the literature.[7,8] All of the mixture gas was obtained as calibration gas grade bottle, traceable to the ASTM standard gas, which enables the providing actual Wobble Index from the ASPEN HYSYS fluid property model.

The relationship between temperature and resistance can be expressed as a simplified Callendar-Van Dusen equation:

$$R_T = R_0(1 + \alpha \times T) \tag{1}$$

Where:

R_T = Resistance at temperature T (Ω)
R_0 = Resistance at T = 0 °C (Ω)
α = Temperature coefficient at T = 0 °C (Ω/Ω/°C)

R_0 and α values were measured to 30.19 ± 0.11 Ω and $(32.4 \pm 0.23) \times 10^{-4}$ Ω/Ω/°C respectively with a 95% confidence level. From the equation, the gas temperature was calculated with a ±1 °C accuracy without use of any additional temperature sensors. A commercially available pressure transducer (Omega Inc.) was used to measure the fuel pressure. The IR sensor was calibrated for all anticipated CH_4 concentrations.

The Wobbe Index of the mixture gas was estimated using a four dimensional curve fitting algorithm. The Multiple Linear Regression algorithm was derived using the MVA (Multi Variate Analysis) function of MATLAB,[9] a commercially available data analysis software packages.

The Wobbe Index, WI, can be derived as follows.

$$WI = f(P, T, E1, E2) \tag{2}$$

Where:

f (P, T, E1, E2) = 4 dimensional curve fitting equation
T = Temperature
P = Pressure
E1 = TCD sensor signal
E2 = IR sensor signal

The Wobbe Indices of the gas mixtures were also calculated using the Aspen HYSYS[10] fluid property model with the Non-Random-Two-Liquid (NRTL) equation as the basis for calculations. Since this calculation is based on the known gas composition of calibration gas, it provide the verification of the accuracy of proposed measurement. The calculated Wobbe Indices were found to be in the same range as the values reported in literature.[11]

3. Results and discussion

Fig. 6 shows the resistance (Z axis, in ohm) of the different gas mixtures (X axis, in percentage CH_4) against the supplied current values (Y axis, in mA) under different pressures. For convenience, thermal conductivity of the gas was measured as the filament resistance of the TCD sensor, since the thermal conductivity is reversely proportional to the surface temperature of the filament in the TCD sensor. The surface temperature of the sensor is a linear function of sensor (filament) resistance, as shown by Equation (1).

The plot shows that as the pressure increases, the measured resistance drops, implying reduced sensitivity (slope of the Resistance vs Current curve) in the resistance measurement. This behavior is expected, since under higher pressures, higher population of the gas molecules, which act as a heat carrier, lead to reduced sensitivity, (i.e. less difference in resistance among different gases). Based on this behavior, it is recommended that the sensor be located in the place with lower fuel pressure, such as downstream of fuel pressure regulator, instead of directly locating inside of the fuel tank.

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[7] "Landfill Gas Energy Basics" by LFG Energy project development handbook, http://www.epa.gov/lmop/index.html.

[8] E Ryckebosch, M Drouillon, H. Vervaeren, Techniques for transformation of biogas to biomethane, Biomass Bioenergy, 35 (5) (2011), pp. 1633–1645.

[9] http://www.mathworks.com/.

[10] http://www.aspentech.com/products/aspen-hysys/.

[11] Laura Bailón Allegue and Jørgen Hinge, "Report, Biogas and bio-syngas upgrading" Danish Technological Institute, December (2012).

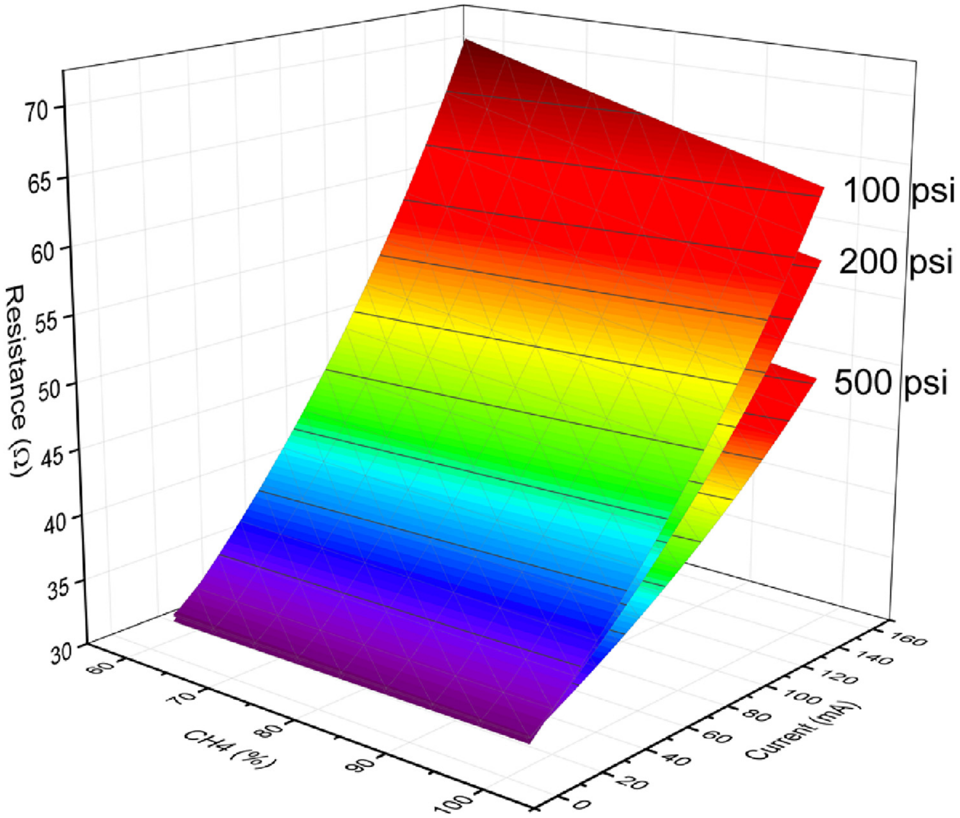

Fig. 6. TCD resistance of gas mixtures at varying currents and pressures.

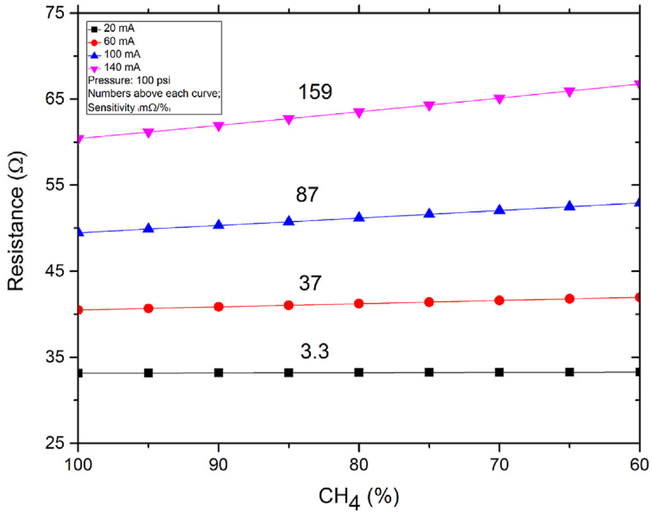

Fig. 7. Relationship of TCD resistance to the gas composition. Pressure = 100 psi. Numbers above each curve shows the slope (sensitivity) of the curve (ΔΩ/Δ%).

It should be noted that there is no measurable difference than 1% in the resistance of the gas mixtures until the TCD excitation current is increased to around 50 mA. This is true for all the different pressures. Fig. 7 shows that at higher TCD excitation currents, the slope of curve increases. A value of 100 mA was chosen as the excitation current for further tests. This value is the median between the 50 mA minimum and the manufacturer's recommended maximum continuous current of 150 mA. This value provides a sensitivity of 87 (slope of the curve, change of the resistance per unit concentration change, ΔmΩ/Δ%), which is large enough sensitivity for the resistance measuring device with 0.1 Ω resolution.

Fig. 8 shows the TCD resistance map for the entire temperature (−20 °C–70 °C) and pressure range (~3600 psi) at 100 mA of TCD excitation current. As the pressure increases the resistance decreases exponentially and plateaus around the value of surrounding temperature, i.e. the value from the equation (1), which is the resistance of the sensor when zero current is supplied. As discussed earlier, the effect of temperature on resistance is in the form of a linear relationship.

Fig. 9 shows the dotted line which represents the optimum equation to predict the Wobbe Index from the measurement of TCD resistance, pressure and temperature shown in Fig. 8. This regression line, obtained using multiple linear regression analysis in MATLAB tool box, shows the predicted Wobble Index value. The equation can be formulated as;

$$Y = \left(0.0102 \times P^{.2105} \times T - 3.701 \times P^{.2155}\right) \times R + 347.85 \times P^{.090} \tag{3}$$

Where:

Y is the Wobbe Index (MJ/Nmˆ3),
P is the pressure in psi,
T is the temperature in Celsius, and
R is the TCD resistance in ohms.

Real Wobbe Index values obtained from the ASPEN analysis from the gas composition for the 4 set of the gas mixture are also shown as square dot in Fig. 9. The deviation from the ASPEN value to the predicted value from equation (3) was maximum 5% throughout the entire temperature and pressure range.

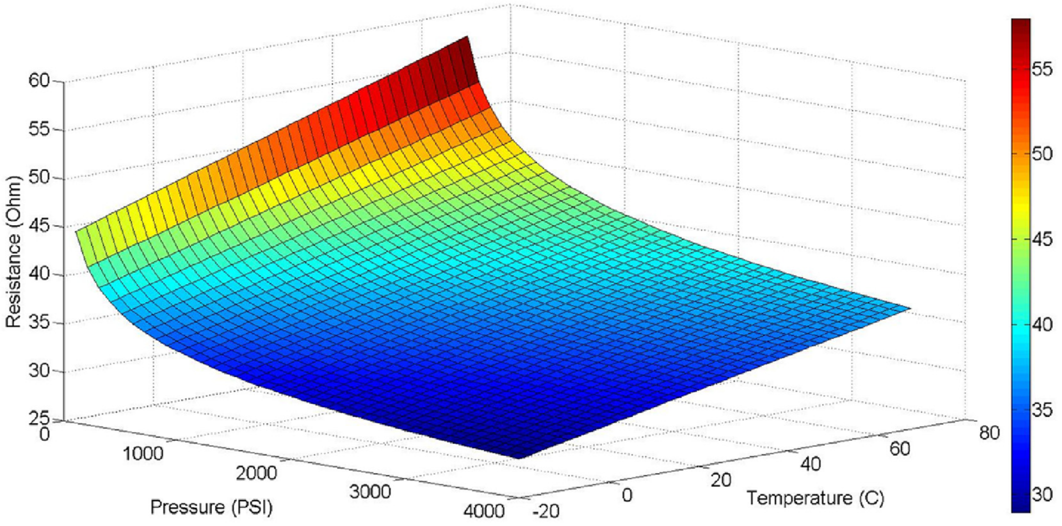

Fig. 8. Relationship of pressure and temperature to resistance.

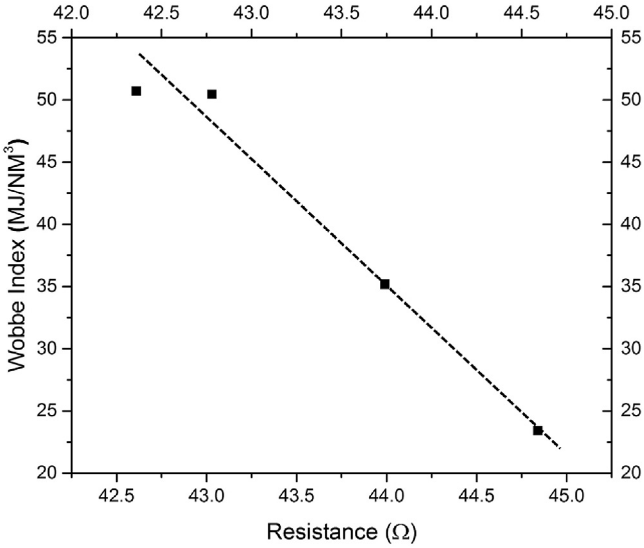

Fig. 9. Relationship of TCD resistance to Wobbe Index at 25 C and 500 psi.

Estimation of Wobbe Index by TCD sensor rely on the fact that CH_4 has the highest thermal conductivity among the components present in the gas mixtures and it constitutes the major component in the natural gas. However other gas species also contribute the thermal conductivity of the gas mixture. The accuracy of the estimated Wobbe Index was significantly increased by constraining the regression further using the data from the IR sensor since the IR sensor provides an independent measurement of CH_4 concentration in the gas mixture. Another important parameter for NG engines, the "Methane Index" can be measured as well since IR sensor provides a direct measurement of CH_4 over the entire temperature and pressure range. By adding the CH_4 measurement data in the algorithm, the accuracy was improved up to 1%. This is mainly because total number of independent variable is increased to 4 from 3. (TCD, IR sensor, Pressure and Temperature), which enables to develop more precise algorithm or regression fit. The optimum implementation algorithm, given in equation (4), uses a weighted average to obtain the corrected Wobbe index. The weighted average was taken between the Wobbe Index from equation (3) and the Wobbe Index as it relates to the CH_4% from Infrared sensor.

The corrected Wobbe Index is:

$$W = \frac{X}{100} * C + \frac{100 - X}{100} * Y \tag{4}$$

Where;

W is the corrected Wobbe Index (MJ/Nmˆ3),
X is the signal from IR sensor in methane mode in CH_4%
C is a correction coefficient summarized in below.
If the X is in the range of 100–90, C = 50
If the X is in the range of 89–70, C = 35
If the X is in the range of 69–50, C = 20
Y is the Wobbe Index from the equation (3).

4. Conclusions

A Wobbe Index sensor for use in NGVs was designed and successfully calibrated using four different gas mixtures. The concept uses a combination of a TCD and an IR sensor and the signals from the sensor are indexed in an algorithm that estimates the Wobbe Index in real time. Successful commercialization of this technology will be a major step towards significantly increasing RNG use in transportation sector. 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 value with a ±5% accuracy from the measured temperature, pressure and thermal conductivity data. The accuracy was further improved to ±1% using the CH_4 concentration data from IR sensor additionally.

The next step in advancing this technology towards commercialization is to build a VNGV engine system that incorporates the Wobbe Index sensor, modified Engine Control Unit (ECU) with the multivariate algorithm and NG engine. The system can be tested in an engine dynamometer, and should be able to alter the injector pulse width in response to the fuel Wobbe Index. An additional feature of importance would be the ability to alter the ignition timing based on the fuel CH_4 content (methane index).

Acknowledgment

This work was supported by the California Energy Commission through Energy Innovation Small Grant No. 57755A/13-02TNG.