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Exhaust Gas and AF Ratio Determination Technique for 2-stroke engines

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Abstract

This paper demonstrates techniques to calculate AF ratio for two-stroke engines. The two models are constructed and verified with up to 155 data from experiment. The first model is designed for hydrocarbon fuel, while the second is primarily designed for oxygenated fuel. Input data for the first model includes five exhaust gas concentrations and fuel formula while the second model requires four more additional data. Results from both models agree well with experimental data. The first model produces results to agree to experimental data within of 6.5% while that of the second model agrees to within 6.0% for hydrocarbon fuel and within 5.2% for oxygenated fuel.

1. Introduction

Up to now two ways to determine air-fuel ratio in engine testing and research activities around the globe are direct measurement of air and fuel flow rates and calculating from data of fuel and exhaust gas compositions. The latter method has been improved and widely accepted to use by research laboratories [1,2]. However this method is more suitable and more accurate for 4-stroke engine than for 2-stroke one. For small 2-stroke engines, difficulties that hinder the determination of AF ratio are direct measurement of airflow rate increasing pressure drop in intake duct. Then intake mixture is enriched and engine performance is affected. Also by nature of 2-stroke engines, there is a short circuit of fresh mixture during scavenging process. Furthermore in reciprocating engines there are suction pulses that affect an accuracy of airflow measurement. Then techniques for calculating of air-fuel ratio of 2-stroke engines from exhaust gas composition become target of interest and research works in this area have been conducted by some research groups, for example, the Queen's University of Belfast [3], Piaggio [4], and KMUTT.

2. Survey of A/F ratio calculation techniques

In 1965, Spindt [5] proposed a method for calculating air-fuel ratio for 4-stroke SI engines. His formula requires details of fuel used and four exhaust gas concentrations (CO_2, CO, HC and O_2). The water-gas equilibrium constant is fixed at 3.5. He compared the calculation results with 243 experimental data tested with 8 liquid fuels and found that his method gives reliable results and it is not sensitive to small errors in exhaust gas analysis.

In 1989, Fukui, et al [6] carried out an extensive study on AF ratio calculation techniques based on Spindt's work and they were primary used for 4-stroke SI engines. They modified Spindt's work by including data of NO in exhaust gas and intake air humidity in the model. They noted that the equilibrium constant was modified by the action of the catalyst and was also affected by the presence of water in the ambient air.

They recommended using direct engine out exhaust gases for determining AF ratio. They also proved that the accurate of their formula to Spindt's formula by using the catalytic converter to convert NO to nitrogen. The results of the comparison showed that the values from Spindt's formula are lower than that of their formula and measured AF ratio.

In 1998, Bresenham, et al [8] published AF ratio formula for 4-stroke SI engines based on Spindt's method but modified it to use with oxygenate fuel and included data of oxides of nitrogen in exhaust gases. They compared it with Spindt's formula, and found that their formula is better than that of Spindt.

Douglas [3] demonstrated the useful technique of calculating AF ratio from exhaust gases for the 2-stroke engines. His technique based on incomplete combustion reaction and included argon and water vapor from atmosphere and used primarily for hydrocarbon fuel without oxygenated additives. He constructed two techniques to calculate AF ratio. The first one was named the overall AF ratio and the second one was the burning zone AF ratio.

The burning zone AF ratio method included trapping efficiency and was suitable for stratified charge engines or direct fuel injection engines. Both techniques required nine input data, i.e. five exhaust gas concentrations (CO, CO_2, HC, O_2, NO), fuel composition, water gas equilibrium constant (K), atmospheric pressure and water vapor pressure at ambient temperature. Although his technique was accurate to calculate AF ratio for two stroke engines, it required many data in calculation process and can be used with hydrocarbon fuel only.

3. Proposal for new models

3.1 First model

The first model was developed and modified from Douglas' work. The main idea was to reduce some input data required in Douglas' model. These reduced data were atmospheric pressure, water vapor pressure, and water gas equilibrium constant. However one additional equation to estimate hydrogen concentration in exhaust gas was included to the model. The model expects to be suitable for two-stroke engines and for hydrocarbon fuels only. The details of the model are described below.

Hydrocarbon fuel is represented by CH_X. The atmospheric air assumes as dry air and water vapor. Dry air is composed of 78.0840% nitrogen, 20.9476% oxygen, 0.9340% argon and 0.0314% carbon dioxide. The products of combustion are considered only for nine exhaust gas species, i.e. CO, CO_2, O_2, H_2O, CH_X, H_2, N_2, NO and Ar.

For the first model, combustion equation is considered as follow:

$$\begin{aligned} CH_X + A\cdot(O_2 + 3.727\cdot N_2 + 0.044\cdot Ar) + B\cdot H_2O \rightarrow \\ a\cdot CO + b\cdot CO_2 + c\cdot O_2 + d\cdot H_2O \\ + e\cdot CH_X + f\cdot H_2 + g\cdot N_2 + h\cdot NO + j\cdot Ar \end{aligned} \quad (1)$$

From the above equation, one can determine AF ratio as in equation (2).

$$A/F = \frac{138.25\cdot A}{12.011 + 1.008\cdot X} = Ka\cdot A \quad (2)$$

In equation (2), AF ratio can be calculated if the value A is known and A can be determined from (3).

$$A = \frac{[CO] + 2\cdot[CO2] + 2\cdot[O2] + [NO]}{2\cdot([CO] + [CO2] + [HC])} + \frac{X}{4}\cdot\frac{([CO] + [CO2])}{[CO] + [CO2] + [HC]}\cdot\left(1 - \frac{[CO]}{[CO] + 3\cdot[CO2]}\right) \quad (3)$$

The value A in (3) is derived from the balances of Carbon, Hydrogen and Oxygen atoms in the combustion equation (1). This can be explained as follow:

Carbon atom balance,

$$1 = a + b + e \quad (4)$$

Hydrogen atom balance

$$x + 2\cdot B = 2\cdot d + x\cdot e + 2\cdot f \quad (5)$$

Oxygen atom balance

$$2\cdot A + B = a + 2\cdot b + 2\cdot c + d + h \quad (6)$$

From the equations (4), (5), and (6), concentrations of species measured directly in exhaust gas are CO, CO_2, CH_x, O_2, and NO. However the concentration of H_2 is not normally analyzed. This can be determined using EPA equation [7] as shown in (7)

$$[H2] = \frac{0.5\cdot X\cdot[CO]\cdot([CO] + [CO2])}{[CO] + 3\cdot[CO2]} \quad (7)$$

The concentration of each component in exhaust gas is related to number of moles in the combustion equation as shown below:

$$[x_i] = \frac{x_i}{n_{tot}}\cdot 100 \quad \text{or} \quad x_i = \frac{n_{tot}[x_i]}{100} \quad (8)$$

where x_i is moles of component i in the exhaust gas

n_{tot} is total number of moles of all components

The total number of moles, n_{tot}, can be determined from the Carbon atom balance equation (4).

$$1 = \frac{n_{tot}[CO]}{100} + \frac{n_{tot}[CO_2]}{100} + \frac{n_{tot}[HC]}{100} \quad (9)$$

$$\therefore \quad n_{tot} = \frac{100}{[CO]+[CO2]+[HC]} \tag{10}$$

Replace (10) in equation (8) and number of moles of component i will be

$$x_i = \frac{[x_i]}{[CO]+[CO2]+[HC]} \tag{11}$$

For instances,

$$a = \frac{[CO]}{[CO]+[CO_2]+[HC]} \tag{12}$$

$$b = \frac{[CO_2]}{[CO]+[CO_2]+[HC]} \tag{13}$$

$$c = \frac{[O_2]}{[CO]+[CO_2]+[HC]} \tag{14}$$

$$e = \frac{[HC]}{[CO]+[CO_2]+[HC]} \tag{15}$$

$$f = \frac{0.5 \cdot X \cdot [CO] \cdot ([CO]+[CO_2])}{([CO]+3\cdot[CO_2])\cdot([CO]+[CO_2]+[HC])} \tag{16}$$

$$h = \frac{[NO]}{[CO]+[CO_2]+[HC]} \tag{17}$$

Replace (15) and (16) into (5) and rearrange. Then the value d can be determined as equation (18) below.

$$d = \frac{X}{2}\cdot\left(\frac{[CO]+[CO_2]}{[CO]+[CO_2]+[HC]}\right)\cdot\left(1-\frac{[CO]}{[CO]+3\cdot[CO2]}\right)+B \tag{18}$$

Replace (12), (13), (14), (17), and (18) in equation (6). Then rearrange and A will be calculated. Equation (3) can be arranged as follow:

$$A = \frac{(K_b + K_c)}{K_d} \tag{19}$$

$$K_b = \frac{[CO]+2\cdot[CO2]+2\cdot[O2]+[NO]}{2} \tag{20}$$

$$K_c = \frac{X}{4}\cdot([CO]+[CO2])\cdot\left(1-\frac{[CO]}{[CO]+3\cdot[CO2]}\right) \tag{21}$$

$$K_d = [CO]+[CO2]+[HC] \tag{22}$$

Then the AF ratio equation is determined from equation (23).

$$A/F = Ka\cdot\frac{(K_b+K_c)}{K_d} \tag{23}$$

In conclusion this model is simple to calculate and requires only five emission concentrations and fuel formula as input data.

3.2 Second model

The second model is developed for two-stroke engines and it primarily designed for oxygenated fuels. However it can also be used with hydrocarbon (non-oxygenated) fuel. The model is different from the first models by considering unburned hydrocarbon in exhaust gas as $C_{X'}H_{Y'}O_{Z'}$. This component significantly affects accuracy of results from two-stroke AF ratio models. The details for the model are shown below.

In the model fuel represents as $C_XH_YO_Z$ and atmospheric air consists of dry air and water vapor. The composition of dry air is the same as mentioned in model 1. The combustion products considered are CO, CO_2, O_2, NO_X, $C_{X'}H_{Y'}O_{Z'}$, H_2O, H_2, N_2 and Ar.

The combustion equation is represented as in (24).

$$\begin{aligned} &C_XH_YO_Z + B\cdot H_2O + \\ &A\cdot(X_{O2}\cdot O_2 + X_{N2}\cdot N_2 + X_{CO2}\cdot CO_2 + X_{Ar}\cdot Ar) \\ &\rightarrow a\cdot CO + b\cdot CO_2 + c\cdot O_2 + d\cdot NO_x + e\cdot C_{X'}H_{Y'}O_{Z'} \\ &\qquad + f\cdot H_2O + g\cdot H_2 + h\cdot N_2 + i\cdot Ar \end{aligned} \tag{24}$$

From (24), the AF ratio can be calculated as shown in (25).

$$A/F = \frac{28.9641 \cdot A}{12.0112 \cdot X + 1.0080 \cdot Y + 15.9994 \cdot Z} \quad (25)$$

It is noted that A/F ratio in (25) will be determined if A is known. The value of A can be calculated from the balances of Carbon, Hydrogen, and Oxygen atoms of the combustion equation (24).

Carbon atom balance:

$$X + A \cdot X_{CO2} = a + b + e \cdot X' \quad (26)$$

Hydrogen atom balance:

$$Y + 2 \cdot B = e \cdot Y' + 2 \cdot f + 2 \cdot g \quad (27)$$

Oxygen atom balance:

$$Z + 2 \cdot A \cdot X_{O2} + 2 \cdot A \cdot X_{CO2} + B = a + 2 \cdot b + 2 \cdot c + d + e \cdot Z' + f \quad (28)$$

The number of moles of some components in exhaust gas can be determined from measuring data as shown below.

$$\begin{aligned} [CO] &= \frac{a}{n_{tot}} \cdot 100 \rightarrow a = \frac{n_{tot} \cdot [CO]}{100} \\ [CO_2] &= \frac{b}{n_{tot}} \cdot 100 \rightarrow b = \frac{n_{tot} \cdot [CO2]}{100} \\ [O_2] &= \frac{c}{n_{tot}} \cdot 100 \rightarrow c = \frac{n_{tot} \cdot [O2]}{100} \\ [NO_X] &= \frac{d}{n_{tot}} \cdot 100 \rightarrow d = \frac{n_{tot} \cdot [NOx]}{100} \\ [HC] &= \frac{e \cdot X'}{n_{tot}} \cdot 100 \rightarrow e = \frac{n_{tot} \cdot [HC]}{X' \cdot 100} \end{aligned} \quad (29)$$

Replace equation (26) with the concentrations of CO, CO_2 and HC from (29) and rearrange to equation (30) as shown below.

$$\begin{aligned} n_{tot} &= 100 \cdot \frac{(X + A \cdot X_{CO2})}{[CO] + [CO_2] + [HC]} \\ &= 100 \cdot k_1 \cdot (X + A \cdot X_{CO2}) \\ k_1 &= \frac{1}{[CO] + [CO_2] + [HC]} \end{aligned} \quad (30)$$

Replace equations (27) and (28) with the concentrations from (29) and the total mole numbers in (30). Then results are shown as (31) and (32).

$$Y + 2 \cdot B = \frac{Y' \cdot [HC]}{X'} \cdot k_1 \cdot (X + A \cdot X_{CO2}) + 2 \cdot f + 2 \cdot g \quad (31)$$

$$Z + 2 \cdot A \cdot X_{O_2} + 2 \cdot A \cdot X_{CO_2} + B = f + \begin{pmatrix} [CO] + 2 \cdot [CO_2] + 2 \cdot [O_2] \\ + [NO_x] + \frac{Z' \cdot [CO]}{X'} \end{pmatrix} \cdot k_1 \cdot (X + A \cdot X_{CO2}) \quad (32)$$

At chemical equilibrium, concentrations of CO_2, H_2, CO and H_2O are related by water gas equilibrium constant (K) as shown below.

$$CO2 + H2 \leftrightarrow CO + H2O$$

$$K = \frac{[CO] \cdot [H2O]}{[CO2] \cdot [H2]} \rightarrow K = \frac{f}{g} \cdot \frac{[CO]}{[CO2]} \quad (33)$$

$$\therefore \; g = f \cdot \frac{[CO]}{K \cdot [CO2]}$$

Replace equation (31) with the value of g in (33) and rearrange to get equation (34).

$$Y + 2 \cdot B = \frac{Y' \cdot [HC]}{X'} 100 \cdot k_1 \cdot (X + A \cdot X_{CO2}) + f \cdot k_3 \quad (34)$$

Number of moles of atmospheric water vapor or B can be calculated from data of partial vapor pressure, atmospheric pressure and relative humidity.

$$\begin{aligned} B &= A \cdot \left(\frac{\phi \cdot Pg}{Pa - \phi \cdot Pg} \right) \\ &= A \cdot k_4 \\ k_4 &= \frac{\phi \cdot Pg}{Pa - \phi \cdot Pg} \end{aligned} \quad (35)$$

where P_g = Partial vapor pressure in atmosphere

P_a = Atmospheric pressure

ϕ = Relative humidity

Replace equation (35) in equations (32), (34) and rearrange. The results are shown below.

$$f = \frac{Y}{k_4} + 2 \cdot A \cdot \frac{k_1}{k_4} - \frac{Y'}{X'} \cdot \frac{k_3}{k_4} \cdot [HC] \cdot (X + A \cdot X_{CO_2}) \quad (36)$$

$$\begin{aligned} f &= Z + 2 \cdot A \cdot X_{O_2} + 2 \cdot A \cdot X_{CO_2} + A \cdot k_1 \\ &- k_3 \cdot (X + A \cdot X_{CO_2}) \cdot ([CO] + 2[CO_2] + 2[O_2]) \\ &- k_3 \cdot (X + A \cdot X_{CO_2}) \cdot \left([NO_X] + \frac{Z'}{X'}[HC] \right) \end{aligned} \quad (37)$$

Replace the value of f from (36) into (37) and rearrange, then the value of A will be determine.

$$A = \frac{\frac{y}{k_4} - Z + k_1 \cdot k_5 \cdot X}{2 \cdot X_{O_2} + 2 \cdot X_{CO_2} + k_4 - 2 \cdot \frac{k_4}{k_3} - k_1 \cdot k_5 \cdot X_{CO_2}} \quad (38)$$

where

$$k_1 = \frac{1}{[CO] + [CO_2] + [HC]}$$

$$k_2 = \frac{[CO]}{K \cdot [CO_2]}$$

$$k_3 = 2 + 2 \cdot k_2$$

$$k_4 = \frac{\phi \cdot P_g}{P_a - \phi \cdot P_g}$$

$$k5 = [CO] + 2 \cdot [CO2] + 2 \cdot [O2] + [NOx] + (Z' - Y'/k4) \cdot \frac{[HC]}{X'}$$

Then the AF ratio in equation (5) will be determined.

4. Experimental results

To verify the accuracy of the models, data of AF ratio were collected from testing of a two-stroke engine and using two fuel types. The testing fuels were hydrocarbon fuel (C_8H_{15}) and oxygenated fuel ($C_{7.7}H_{14.55}O_{0.05}$).

Test results of AF ratio in a range of 10-26 for 155 data were collected using hydrocarbon fuel. For oxygenated fuel the values of AF ratio in a range of 10-18 were collected for 35 data. Fig. 1 shows relationship of 155 measured AF ratio data using hydrocarbon fuel and calculated results using the model 1. It is noted that results from the model 1 agree well with that from measurement. In Fig. 1 upper and lower limited lines of 6.5% are also shown. It is seen that all 155 data are situated within the limits.

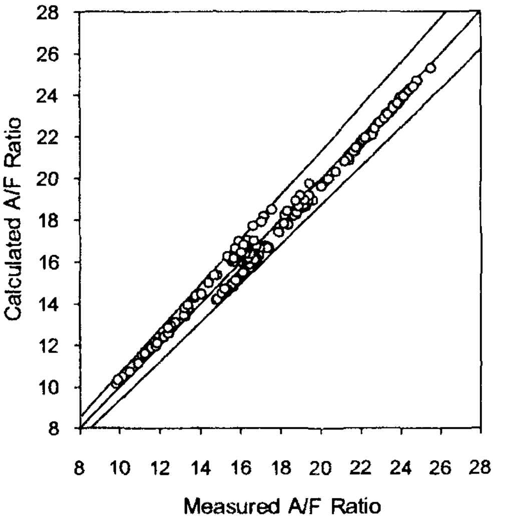

Fig.1 Comparison of calculated A/F ratio from model 1 with measured A/F ratio from a two-stroke engine using C_8H_{15} as fuel.

Fig. 2 shows relationship of 155 measured AF ratio data using hydrocarbon fuel and calculated results using the model 2. It is seen that the calculated data also agree well with the measured ones. It is observed that all 155 data are located within the limited lines of 6.0%.

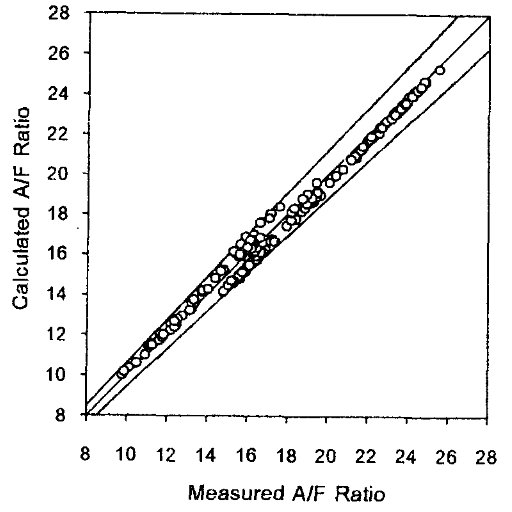

Fig.2 Comparison of calculated A/F ratio using the model 2 with measured A/F ratio from a two-stroke engine using C_8H_{15} as fuel.

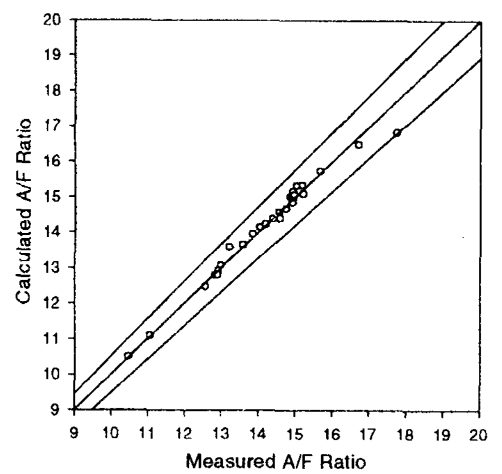

Fig.3 Comparison of calculated A/F from model 2 with measured A/F from a two-stroke engine with $C_{7.7}H_{14.55}O_{0.05}$ as fuel.

Fig. 3 shows relationship of 35 measured AF ratio data using oxygenated fuel ($C_{7.7}H_{14.55}O_{0.05}$) and calculated AF ratio using the model 2. It is noted that calculated data agree well with the measured ones. It is seen that all data are located within the 5.2 % limited lines.

5. Conclusions

Two simple models for calculating AF ratio of two-stroke engines using exhaust gas composition were constructed based on the model in literature. The first model is designed to use with non-oxygenated gasoline. It requires input data of five exhaust gas compositions and fuel formula. Although the second model is primarily designed for oxygenated fuels, it can also be used with non-oxygenated fuel. However it requires input data more than the first model. Results from both models agree well with experimental data. The first model produces results to agree to experiment within of 6.5% while that of the second model agree to experimental results within 6.0% of hydrocarbon fuel and within 5.2% for oxygenated fuel. Two models are expected to be useful tool for two-stroke engine research in many laboratories.

6.Acknowledgments

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