

Impact of Reformed Ethanol on the Volumetric Efficiency in I.C. Engines

2010-01-1465

Published
05/05/2010

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ABSTRACT

This article presents a set of formulas for estimating the impact of reformed ethanol fuel on volumetric efficiency in I.C. engines. Both partial and complete usages of reformed ethanol fuel are discussed.

Analysis suggests that volumetric efficiency drastically decreases as the level of fuel reforming increases in S.I. engines. Such impact on volumetric efficiency is reduced when the reformed fuel is partially used in diesel engines.

A formula for calculating the impact of intake air temperature variation on volumetric efficiency is also presented. This formula is validated against engine simulation on factors such as engine load, speed, displacement, intake air temperature and reformed fuel temperature.

Validation results show a maximum of 0.5% error, indicating an accurate approximation and hence high feasibility of this formula.

The calculation predicts a decrease of 3-7% in volumetric efficiency caused by temperature variation due to high temperature reformed ethanol fuel, which is consistent with engine simulations.

Keywords

reformed ethanol, I. C. engine, volumetric efficiency, temperature variation

INTRODUCTION

Hydrogen-rich gases from ethanol steam reforming can be supplied as fuel for internal combustion engines. The mechanism and thermodynamics of ethanol steam reforming reactions have been studied extensively^{[1] [2] [3]}. The researches on on-board reforming of ethanol for engines have also been studied^{[4] [5]}.

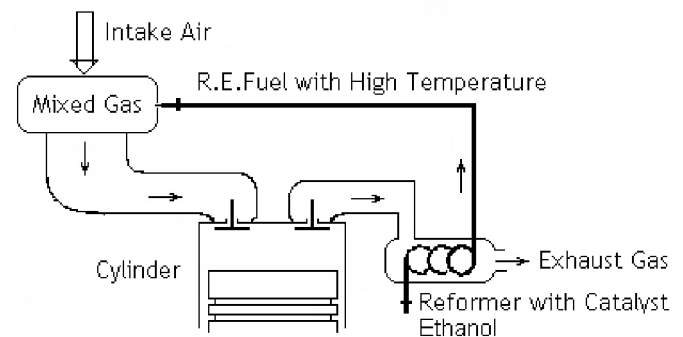


Fig 1. Schematic of Reformed Ethanol Engine System

Figure 1 shows the schematic of a kind of reformed ethanol engine (R.E. engine), which consists of a baseline of S.I. engine and a set of ethanol reforming & fuel supply system. The reformer with catalyst, assembled on the exhaust manifold, is heated by exhaust gas. Reformed ethanol fuel (R. E. fuel) with high temperature is mixed with air and then routed into cylinders via the intake manifold.

On-board R. E. fuel engines are potential strategy for using bio-fuel in transport facilities. Hydrous-ethanol instead of pure ethanol is used as fuel, which could remarkably reduce

its energy consumption in ethanol production by saving its rectifying process. The combustion in cylinder could be improved due to usage of hydrogen-rich gaseous fuel. There are still some problems for R. E. fuel engines such as absence of appropriate catalysts, combustion performance, and the reduction of the power output and so on.

It has been noticed that the volumetric efficiency of gaseous fuel engines decreases [6] [8] [9], which would result in the reduction of the power output. Compared with that of such traditional engine as gasoline engine and diesel engine, the volumetric efficiency of R.E. engine would significantly reduce. One of the reasons is that the mole of R.E. fuel increases and more room of the cylinders are occupied by the premixed gaseous fuel. The mole of R.E. fuel is closely related with its components and the concentration of each component, which varies with the working conditions, and the levels of fuel reforming, and the concentration of ethanol and so on.

Based on both assumptions, Equal Energy assumption, where R.E. fuel substitutes the fuel of baseline engines such as gasoline or diesel fuel in term of equal energy, and Equal Mole assumption, where the total mole of intake charge for R.E. engine is equal to that for baseline engine, a set of equations have been introduced, by which the impact of the mole of R.E. fuel on volumetric efficiency in I.C. engines can be calculated. The equations can be applied for both partial and complete usage of R.E. fuel in both gasoline and diesel engines. Moreover, the equations in this paper have wider application than the formulas in reference [9] due to not deriving from some specified reforming reactions.

Another reason of volumetric efficiency reduction in R. E. engines is higher intake temperature due to R.E. fuel with high temperature from the reformer. There is a complicated process with heat transfer while the gas flows into the cylinders via the intake manifold. The process can be calculated by some simulation software, but this kind of simulation aims at specific working conditions of specific engines instead of a general description for the process. In the paper, a simple formula is tried to be built for calculating the impact of intake air temperature variation on volumetric efficiency.

FORMULAS OF INFLUENCE ON VOLUMERIC EFFICIENCY

There are some other assumptions for the formulas in this section in addition to both Equal Energy and Equal Mole assumptions. The first one is that only stable working conditions of engine are considered. The second is that the thermal conditions of intake process for R.E. engine is approximately similar to that for baseline engine, and the

third is that exhaust flow resistance due to the reformer is not considered.

Obviously, the assumptions of Equal Energy, Equal Mole and the stable working conditions of engines are considerably reasonable, but the second and the third are only because of simplification of formula derivation in this section. In fact, either intake or exhaust conditions is quite different between R.E. engines and baseline engines. The effect of R.E. fuel's temperature on volumetric efficiency will be discussed in detail in following sections.

The relationship between the fuel consumption of R.E. engine and that of the baseline engine can be expressed as a formula in term of Equal Energy assumption;

$$M'_f = \frac{H_u}{H'_u} M_f \quad (1)$$

Where M_f and M'_f are the fuel consumptions of both baseline engine and R.E. engine respectively, and H_u and H'_u are LHV (Low Heating Value) of the fuel for the baseline engine and for R.E. fuel respectively.

Based on Equal Mole assumption, the mole reduction of intake charge in cylinder is equal to the mole increase of gaseous fuel in cylinder, which is given by,

$$\frac{1}{\mu_a} \cdot \Delta M_a = \left(\frac{H_u}{H'_u} \cdot \frac{1}{\mu_f} - \frac{1}{\mu_g} \right) \cdot M_f \quad (2)$$

Where ΔM_a ($\Delta M_a = M'_a - M_a$) is the mass increase of intake charge in the cylinder at the end time of intake process, and M_a and M'_a are the mass amounts of intake charge in the cylinder at the end time of intake process for the baseline engine and for R.E. fuel respectively, and μ_f and μ_g are MMW (the Mean Molecular Weight) of the R.E. fuel and gasoline fuel respectively.

Compared with that of the baseline engine, the influence of R. E. fuel on the volumetric efficiency of engines is given by:

$$\frac{\eta'_v}{\eta_v} = \frac{M'_a}{M_a} = 1 - \frac{\Delta M_a}{M_a} = 1 - \frac{\mu_a}{\lambda \cdot L_o} \cdot \left(\frac{H_u}{H'_u} \cdot \frac{1}{\mu_f} - \frac{1}{\mu_g} \right) \cdot \quad (3)$$

Where η_v and η'_v are the volumetric efficiency of both baseline engine and R.E. engine respectively, and μ_a is

MMW of air; and λ is excess air coefficient, and L_0 is stoichiometric air-fuel ratio.

By similar deducing, there are some other formulas like following [formula \(4\)](#), [5](#), [6](#), [7](#), [formula \(8\)](#).

Besides some main components including carbon monoxide (CO), and hydrogen (H₂), and carbon dioxide (CO₂) and some others, there are ethanol and the water in R.E. fuel called residue ethanol and residue water which are not involved in reforming reaction. While the residue ethanol and the water in the R.E. fuel are not probably gaseous state (which depending on the intake temperature), **the effect of residue liquid ethanol and water should be taken into account**, which is given by,

$$\frac{\eta'_v}{\eta_v} = 1 - \frac{\mu_a}{\lambda \cdot L_0} \cdot \frac{H_u}{H'_u} \cdot \left[\frac{1}{\mu_f} - \frac{(1-\alpha')(1-\beta)}{\mu_w} - \frac{\alpha'(1-\beta)}{\mu_e} - \frac{1}{\mu_g} \right] \quad (4)$$

where μ_w and μ_e are MMW of water and ethanol respectively; β is reforming efficiency which is the ratio of amount of ethanol being reformed to total amount of ethanol fuel in reforming reaction (weight/weight); α and α' are the mass concentrations of both ethanol and residual ethanol after the reforming reaction.

While **blending partial R.E. fuel** is used in gasoline engine, the equation is given by;

$$\frac{\eta'_v}{\eta_v} = 1 - \frac{\psi \cdot \mu_a}{\lambda \cdot L_0} \cdot \left(\frac{H_u}{H'_u} \cdot \frac{1}{\mu_f} - \frac{1}{\mu_g} \right). \quad (5)$$

Where ψ is the ratio of blending R. E. fuel to total energy including baseline engine fuel and R. E. fuel blended in term of equal energy.

While **blending partial R.E. fuel** is used in gasoline engine and **the effect of residue liquid ethanol and water is taken into account**, which is given by,

$$\frac{\eta'_v}{\eta_v} = 1 - \frac{\psi \cdot \mu_a}{\lambda \cdot L_0} \cdot \left[\frac{H_u}{H'_u} \cdot \left(\frac{1}{\mu_f} - \frac{(1-\alpha')(1-\beta)}{\mu_w} - \frac{\alpha'(1-\beta)}{\mu_e} \right) - \frac{1}{\mu_g} \right] \quad (6)$$

While **blending partial R.E. fuel** is used in diesel engine, the equation is given by;

$$\frac{\eta'_v}{\eta_v} = 1 - \frac{\psi \cdot \mu_a}{\lambda \cdot L_0} \cdot \frac{H_u}{H'_u} \cdot \frac{1}{\mu_f} \quad (7)$$

While **blending partial R.E. fuel** is used in diesel engine and **the effect of residue liquid ethanol and water is taken into account**, the equation is given by;

$$\frac{\eta'_v}{\eta_v} = 1 - \frac{\psi \cdot \mu_a}{\lambda \cdot L_0} \cdot \frac{H_u}{H'_u} \cdot \left[\frac{1}{\mu_f} - \frac{(1-\alpha')(1-\beta)}{\mu_w} - \frac{\alpha'(1-\beta)}{\mu_e} \right] \quad (8)$$

The formulas in this section are applicable to the wider scope because of being not based upon some of specified reforming reactions.

The [formula \(3\)](#) and [formula \(7\)](#) are the basic forms of these formulas, which can be applied to some gaseous fuel such as LPG, CNG, and LNG etc. just by determining LHV H'_u and MMW μ_f of the fuels.

IMPACT OF R.E. FUEL AND THE COMPONENTS OF R.E. FUEL ON VOLUMERIC EFFICIENCY

Most of the parameters in the [formulas \(3\)](#), [4](#), [5](#), [6](#), [7](#), [\(8\)](#) can be obtained easily and some parameters are shown in [table 1](#) ^[7].

Table 1. Physical Parameters of some fuels and components of R. E. fuel^[7]

	LHV (kJ/kg)	Stoichiometric A/F ratio	MMW (kg/mol)
ethanol	26800.0	9.0	46.0
gasoline	43500.0	14.5	110.0
diesel	42700.0	14.6	170.0
air	/	/	29.0
water	/	/	18.0
hydrogen (H ₂)	120000.0	34.3	2.0
carbon monoxide	10100.0	2.5	28.0
carbon dioxide	/	/	44.0
methane	55625.0	16.7	16.0

MMW of R.E. fuel (μ_f) is obtained from the molar concentration and the molecular weight of each component in R.E. fuel as following equation;

$$\mu_f = \sum x_i \cdot \mu_i \quad (9)$$

Where x_i is molar concentration of each component; and μ_i is molecular weight of each component;

LHV of R.E. fuel (H'_u) is obtained from the mass concentration and LHV of each component in R.E. fuel as following;