ANALELE UNIVERSITĂȚII
"EFTIMIE MURGU" REȘIȚA
ANUL XVII, NR. 2, 2010, ISSN 1453 - 7397

Adrian Irimescu

Study of Volumetric Efficiency for Spark Ignition Engines Using Alternative Fuels

One of the most important parameter for spark ignition engines is volumetric efficiency, as it directly influences specific power output. Several definitions of this parameter are studied from a theoretical point of view, taking into consideration the use of alternative fuels. The influence of using gasoline-bioethanol blends is investigated, as well as the effect of fuelling spark ignition engines with methane, liquefied petroleum gas and hydrogen. Bioethanol features the highest volumetric efficiency, while gaseous fuels cause a drop in specific power output compared to gasoline operation.

***Keywords**: spark ignition engines, volumetric efficiency, alternative fuels*

1. Introduction

As most spark ignition (SI) engines are naturally aspirated, great efforts are undertaken to increase their volumetric efficiency. Four valves per cylinder instead of two, variable timing [1], [2] and intake systems without throttle valves [3] are all designed to decrease pumping losses and increase specific power output.

Biofuels are set to play a major role in the future energy mix, and their use in SI engines raises specific problems [4], [5], [6]. While the cooling effect of using ethanol mixed with gasoline increases volumetric efficiency, fuelling engines with liquefied petroleum gas (LPG) or methane leads to a drop in power output.

Several definitions of volumetric efficiency are presented, and theoretical studies regarding the influence of using alternative fuels were undertaken. Using the results provided by studies such as the one developed in this paper, valuable solutions for optimum operating parameters can be identified. As biofuels will most likely be used in large quantities in the future, the effects of using this fuel category in SI engines should be carefully studied. By employing the thermodynamic model presented, various influences can be studied when fueling SI engines with bioethanol or other alternative fuels.

2. Thermodynamic model

Several definitions for SI engines volumetric efficiency are given in the literature. They refer to the entire intake system, comprising of air filter, inlet tract, throttle valve, intake runners, manifold and intake valve or just specific portions. The basic principles are referring to air-fuel mixture mass retained inside the cylinder at the end of the intake process [7], [8], or just the mass of air [9].

If the mass of air retained inside the cylinder is considered, volumetric efficiency is defined by equation (1),

$$\eta_v = \frac{m_a}{\rho_a \cdot V_d}, \tag{1}$$

where m_a is the mass of air retained inside the cylinder after the intake valve closes, in kg, ρ_a ambient air density measured in kg/m^3, and V_d displacement, in m^3.

When considering the mass of air-fuel mixture drawn into the cylinder, volumetric efficiency is defined by equation (2),

$$\eta_v = \frac{p_i}{p_a} \cdot \frac{T_a}{T_i} \cdot \frac{\varepsilon}{\varepsilon - 1} \cdot \frac{1}{1 - \varphi_d + \gamma_e}, \tag{2}$$

where η_v is the volumetric efficiency, p_i mixture pressure at the end of the intake stroke, p_a ambient pressure, both measured in Pa, T_a ambient temperature, T_i mixture temperature at the end of the intake stroke, both in K, ε compression ratio, φ_d dynamic effects coefficient and γ_e exhaust gas coefficient defined as $\gamma_e = \nu_e / \nu_m$, with ν_e the number of exhaust gas moles inside the cylinder at the end of the intake process and ν_m the moles of air-fuel mixture retained inside the cylinder. Coefficient φ_d, introduced to account for dynamic effects such as pressure waves inside the intake manifold and ram effect, was determined based on experimental values.

Both definitions can be used to evaluate the entire intake system or just certain components. For the case studies presented in this paper, the volumetric efficiency of the intake system as a whole was considered.

Figure 1 shows how the volumetric efficiency defined with equation (2) varies with engine speed and throttle valve opening. Pressure levels inside the cylinder at the end of the intake stroke (p_i) were calculated based on a simple hydrodynamic model. Considering quasi-steady flow, the pressure drop along the intake tract was calculated using equation (3),

$$\Delta p = \zeta \cdot \rho \cdot \frac{w^2}{2}, \tag{3}$$

where Δp is the pressure drop across the local hydrodynamic resistance, measured in Pa, ζ local resistance coefficient, ρ fluid density, in kg/m^3, w flow speed before the hydrodynamic resistance, measured in m/s.

Mixture temperature (T_i) was calculated taking into consideration heat transferred from the intake components to the air and the heat flux transferred from different engine components to the air-fuel mixture, as well as the cooling effect of fuel evaporation. Only convective heat transfer was considered, as radiation and conductive transfer are insignificant. Coefficient values for convective heat transfer (C_c) were calculated using equation (4),

$$C_c = 86{,}389 \cdot \frac{p^{0,8} \cdot w^{0,8}}{T^{0,546} \cdot d^{0,2}}, \qquad (4)$$

where C_c is the convective heat transfer coefficient, in W / (m^2 · K), p local static pressure measured in bar, w flow speed in m/s, T fluid temperature, measured in K, and d local diameter, in m.

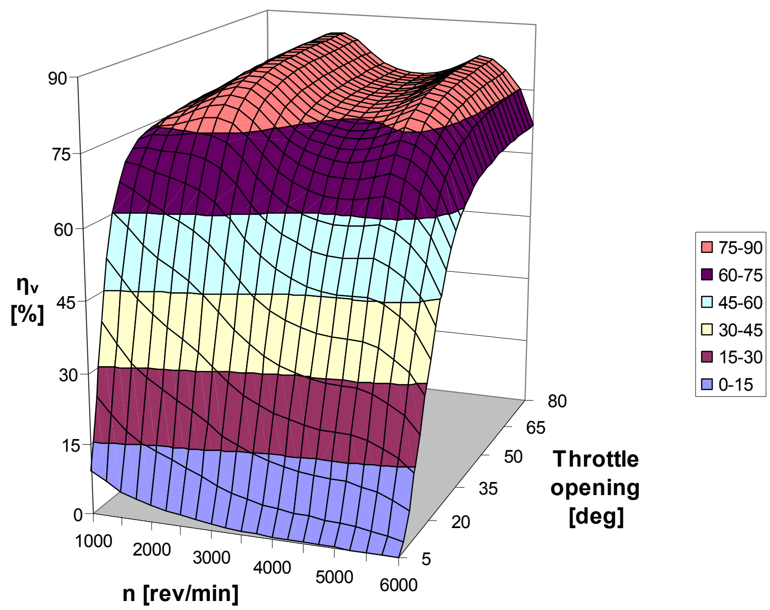

Figure 1. Volumetric efficiency calculated with equation (2) at different engine speed values and throttle opening angles, for gasoline, stoichiometric air-fuel ratio

3. Results and discussions

A port injection engine with a total displacement of 1998 cm^3 was considered for calculations. Main characteristics of this engine are presented in table 1.

Case studies for gasoline and alternative fuels were calculated for the same atmospheric conditions, with 1000 mbar ambient pressure, 15 °C air temperature and 50 % relative humidity. As stoichiometric air-fuel ratios are employed in port injection engines throughout most of their operation, all studies were conducted making this assumption.

Table 1. Case study engine specifications

Maximum power	85 kW at 5200 rev/min
Maximum torque	170 Nm at 2600 rev/min
Displacement	1998 cm^3
Bore x Stroke	86 x 86 mm
Compression ratio	9.2
Fuel system	Port injection, 2,5-3 bar rail pressure
Emissions control	Oxygen sensor and catalytic converter

Figure 2 shows full load calculated volumetric efficiency using equation (1), throughout the entire engine speed range, from 1000 to 6000 rev/min. Gaseous fuels show the lowest values, while ethanol ensures maximum volumetric efficiency for the entire engine speed range. This trend was confirmed experimentally, as SI engines exhibit a drop in power when fueled with LPG, methane or hydrogen. As the fuel is mixed with air after the liquid has evaporated, gasoline and ethanol will feature a denser charge as a result of the cooling effect during evaporation. Ethanol increases volumetric efficiency as it has a higher latent heat of vaporization, resulting in a cooler air-fuel mixture compared to gasoline.

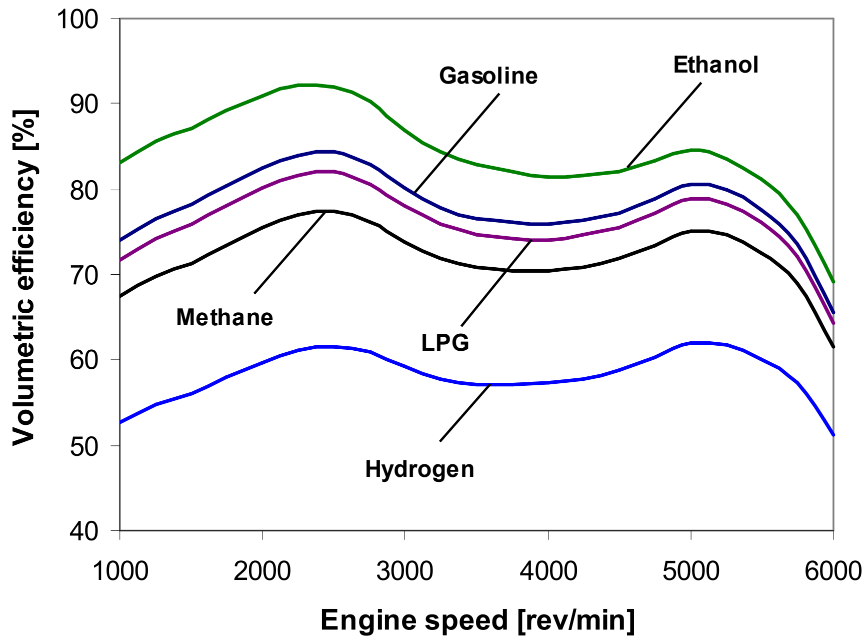

Figure 2. Volumetric efficiency calculated with equation (1) at full load for different engines speed values and fuel types, stoichiometric air-fuel ratio

The power loss when using methane can be partially recovered by employing an advanced timing. This operating strategy is possible due to the fact that compared to gasoline, methane has a much higher octane rating, thus greatly reducing knock tendency.

Table 2. Intake parameters* for different fuel types

Fuel	**Volumetric efficiency**				**Intake charge energy content**	
	Equation (1)		Equation (2)			
	η_v [%]	$\Delta\eta_v$ [%]	η_v [%]	$\Delta\eta_v$ [%]	Q_{mix} [kJ]	ΔQ_{mix} [%]
Gasoline	84,29	-	85,87	-	1,49	-
Ethanol	91,94	+9,08	98,33	+14,51	1,66	+11,41
LPG	81,98	-2,74	84,87	-1,16	1,45	-2,68
Methane	77,37	-8,21	85,42	-0,52	1,35	-9,39
Hydrogen	61,62	-26,89	87,22	+1,57	1,29	-13,42

* calculated at full load, engine speed 2500 rev/min, stoichiometric air-fuel ratio

Table 2 shows results for full load, 2500 rev/min engine speed. In addition to the volumetric efficiency calculated with equations (1) and (2), energy content for the air-fuel mixtures was calculated. Maximum volumetric efficiency was obtained for ethanol. Also, the ethanol-air charge at the end of the intake process has the highest energy content, with an increase of over 11 % compared to gasoline. This calculated value is very close to a ~ 10 % power increase when using pure ethanol to power SI engines instead of gasoline. Power loss for LPG and methane operation also shows close values to the ones calculated for air-fuel energy content. Hydrogen features the lowest intake charge energy content, over 13 % lower than gasoline. Also, hydrogen combustion is quite violent, therefore power loss is even larger as the mixture has to be leaned out when using this fuel. An interesting result is that equation (2) predicts an increase in volumetric efficiency of almost 2 % compared to gasoline. This is a result of a lower pressure drop across the intake valve and thus a higher pressure level at the end of the intake stroke. Also, stoichiometric air-fuel mixtures contain very little hydrogen, as for every 1 kg of fuel, 34,47 kg of air are required.

4. Conclusions

A simple thermodynamic model was developed for calculating SI engines volumetric efficiency. Two equations were used for calculating this intake parameter. Also, the energy content was calculated for comparing different fuel types.

Several fuelling strategies were investigated, when using gasoline, bioethanol, LPG, methane and hydrogen. Results show the highest volumetric efficiency for ethanol. Based on the energy content of the intake charge, hydrogen shows the lowest values, and predicted power loss for LPG and methane was close to measured power output compared to gasoline. For this reason, calculating the energy content of the intake charge is the best method for comparing alternative fuels used in SI engines.

References

[1] Atashkari K., Nariman-Zadeh N., Gölcü M., Khalkhali A., Jamali A., *Modelling and multi-objective optimization of a variable valve-timing spark-ignition engine using polynomial neural networks and evolutionary algorithms*. Energy Conversion and Management, Volume 48, Issue 3, March 2007, 1029-1041.

[2] Turin R. C., Zhang R., Chang M. F., *Volumetric Efficiency Model for Variable Cam-Phasing and Variable Valve Lift Applications*. Electronic Engine Controls, 2008 SAE SP no. 2159, 2008, New York, USA, 169-180.

[3] Negurescu N. N., Pana C., Popa M. G. D., Racovitza C. C. A., *Variable Valve-Control Systems for Spark Ignition Engine*. SAE 2001 World Congress, March 2001, Detroit, MI, USA, available online www.sae.org, SAE Document Number 2001-01-0671.

[4] Engler-Pinto C. M., Nadai L., *Volumetric Efficiency and Air-Fuel Ratio Analysis For Flex Fuel Engines*. Published October 2008, available online www.sae.org, SAE Document Number 2008-36-0223.

[5] Benvenho A. R. V., Li R. W. C., Gruber J., *Polymeric electronic gas sensor for determining alcohol content in automotive fuels*. Sensors and Actuators B: Chemical, Volume 136, Issue 1, 2 February 2009, 173-176.

[6] Irimescu A., *Full Load Performance of a Spark Ignition Engine Fueled with Gasoline-Isobutanol Blends*. Analele Universităţii "Eftimie Murgu" Reşiţa, Fascicola Inginerie, Anul XVI, 2009, Nr. 1, 151-156.

[7] Grünwald B., *Teoria, calculul şi construcţia motoarelor pentru autovehicule rutiere*. Editura Didactică şi Pedagogică Bucureşti, Romania, 1980, 51-67.

[8] Băţaga N., Burnete N., Căzilă A., Rus I., Sopa S., Teberean I., *Motoare cu ardere internă*. Editura Didactică şi Pedagogică Bucureşti, Romania, 1995, 28-41.

[9] Heywood J. B., *Internal Combustion Engines Fundamentals*. Mc-Graw Hill Series in Mechanical Engineering 1988, 53-54.

Address:

- Assist. Prof. Dr. Eng. Adrian Irimescu, "Politehnica" University of Timisoara, Mihai Viteazul no 1, Timisoara, iamotors@yahoo.com