Analysis of the impact on volumetric efficiency in the use of biogas

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ABSTRACT

This article investigates the effects of intake manifold pressure and engine speed on the volumetric efficiency of an internal combustion engine. The study also examines the impact of biogas and different temperatures on volumetric efficiency. Through analysis, it's verified if the volumetric efficiency of the engine decreases when using biogas as fuel, due to the presence of water vapor and carbon dioxide. Adjustments to the air-fuel ratio and ignition timing to ensure optimal combustion and maximum volumetric efficiency are analyzed. The results of the analysis are presented in the form of graphs, which provide a clear understanding of the relationship between the parameters studied and the volumetric efficiency of the engine. The study provides valuable insights for the development of efficient engines powered by biogas in different operating conditions.

INTRODUCTION

The focus on emissions and efficiency in recent research on internal combustion engines is due to the ever-increasing legal requirements regarding emission levels and the highly competitive automotive market, which is always seeking new solutions. The study of the impact on volumetric efficiency of alternative fuels is part of this context, as it directly affects the performance of various engine parameters, including efficiency and emission levels. The use of renewable fuels such as biogas generates several benefits beyond environmental ones, such as the use of by-products and job creation.

A widely used strategy to improve the performance and emissions of internal combustion engines is modeling and control. By managing the action of actuators based on signals measured by sensors, a controller can be developed that operates under optimal conditions, in order to obtain the best performance for a particular fuel use. This process begins with model design, gathering data that demonstrate the behavior of the engine.

Modeling air intake in an internal combustion engine allows the estimation of pressure in the intake manifold, a variable of significant importance in various engine and electronic control unit (ECU) operations, such as emissions control and torque estimation. To model air intake, the volumetric efficiency of the engine must be known, which depends on several variables involved in the air intake process. Therefore, an analysis of the impact of these variables is necessary for modeling and control design.

Volumetric efficiency for a biogas-fueled engine will be studied in this article. The next sections are arranged in the following order. Section 2 explains the methodology for obtaining volumetric efficiency. In section 3, the modeling of volumetric efficiency in an internal combustion engine is detailed. In section 4, experiments carried out with the consequent discussion are presented. The article ends with acknowledgments and conclusion.

METHODOLOGY

First, a literature review is conducted to study the main variables that impact volumetric efficiency. A laboratory is then properly equipped to allow experiments to be conducted to ascertain the impact of various variables on volumetric efficiency. Curves are then obtained with the aim of demonstrating the results.

MODELING

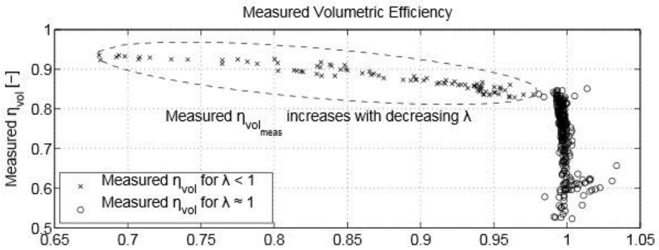
The volumetric efficiency of an engine can be defined as the ratio of the mass of gas admitted by the cylinder to the mass that would occupy the displaced volume having the same density present in the intake manifold [1].

Several factors influence volumetric efficiency, including fuel properties, heat transfer, intake manifold pressure, duct length, engine angular velocity, valve timing, recirculation rate, air/fuel ratio, cylinder-to-cylinder vibrations through the crankshaft, injection location, valve friction, engine geometry, intake system friction, flow turbulence, RAM effect in the intake duct, back-flow, intake manifold temperature, resonance in the intake manifold, residual gas in the cylinder, and compression ratio [2][1][3].

The researcher should therefore select the parameters that they consider necessary for modeling, choosing an adequate quantity so as not to overload the volumetric efficiency identification test. Guzzella and Onder recommend the use of only intake manifold pressure and engine speed [2]. John J. Moskwa adds intake manifold temperature to his model [4]. A study on the influence of λ on volumetric efficiency carried out by Andersson and Eriksson can be found in [5].

For simplicity in conducting the tests, we do not recommend considering intake manifold temperature, as it is a variable that is difficult to manipulate, and satisfactory results can be obtained even without considering it. By analyzing [5], the reader may be convinced to use λ as a parameter, adopting a linear correction factor in λ, as it is an easily manipulable variable. However, it should be noted that only for large λ excursions do we have significant changes in volumetric efficiency.

Figure 1: Volumetric efficiency measured as a function of the air/fuel equivalence ratio for values of λ<1 and λ≈1.



Source: [5]

We find in [2] an empirical method for determining volumetric efficiency. As a first approximation, we will:

$$\lambda_\iota(p_{adm}, \omega_e) = \lambda_{\iota p}(p_{adm}) \cdot \lambda_{\iota\omega}(\omega_e) \qquad (1)$$

Assuming perfect gases, isentropic processes, and an ideal Otto cycle, we can model the volumetric efficiency factor dependent on the intake manifold pressure through the back-flow phenomenon as [6]:

$$\lambda_{\iota p}(p_m) = \frac{V_c + V_d}{V_d} - \left(\frac{p_{exh}}{p_{adm}}\right)^{1/\kappa} \cdot \frac{V_c}{V_d} \qquad (2)$$

In which,
V_c: Compression ratio;
V_d: Displacement volume;
p_{exh}: Exhaust manifold pressure;
p_{adm}: Intake manifold pressure.

Using equations (1) and (2), we can identify the volumetric efficiency of the engine by varying the engine speed, thereby reducing the number of experiments. As discussed earlier, the researcher can also add a correction factor that is a function of λ, based on [5].

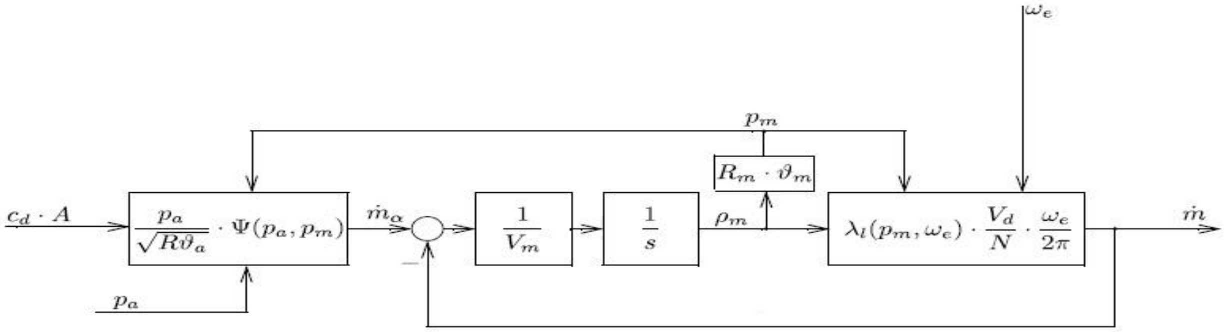
Note that to identify the volumetric efficiency, the mass flow rate through the cylinder must be known. We suggest that the reader employ the same procedures used to identify the mass flow rate in experiments with the valve. Conduct the test under steady-state conditions to more accurately assume that the masses entering each cylinder are equal, which will allow you to divide the engine's intake mass by the number of cylinders to determine the average mass flow rate in each cylinder.

To implement the models in simulation hardware, the air intake model will be presented in a block diagram. The continuous-time diagram is reproduced in Figure 2.

In this diagram, note that the block referring to the throttle valve receives as input the product of the valve's discharge coefficient by its area, the intake manifold pressure, and ambient pressure. The ECU designer can mount the ambient pressure sensor directly on the ECU panel [2]. The use of this sensor is recommended because it is not expensive. This block outputs the air flow rate exiting the valve. Note that the block relating the throttle valve actuation signal to the opening area is not illustrated, but such a block must be implemented. Note that we are assuming that the intake manifold pressure is initially zero, and this value will be updated as the engine operates.

The following adder represents the flows entering the intake manifold. We have the inlet flow (flow coming from the throttle valve, with a positive sign) and the outlet flow (flow entering the cylinder, with a negative sign), and the sum of these flows, with their respective signs, represents the derivative of the mass stored in the manifold. This derivative will pass through a block that divides it by the manifold volume, resulting in the derivative of the density that will then pass through an integrator block, resulting in the density of the gas mixture stored in the manifold. This density then passes through a block that represents the Gas Law and outputs the pressure in the intake manifold. At this point, the pressure in the intake manifold is updated.

Figure 2: Continuous diagram of the air intake system.



Source: [2]

Next, we have the block that represents gas pumping. This block estimates the flow entering the cylinder based on the density of the gas mass stored in the intake manifold and the engine speed, whose value is provided by the crankshaft position sensor.

EXPERIMENTAL STRUCTURE

In this experiment, the engine was used coupled to a bench dynamometer to adjust the engine speed. The intake pressure, injection timing and ignition angle are controlled using the INCA software, and the data were recorded in Matlab software. A programmable ECU was used, which communicates with the INCA software. The engine used is the EA 111 VHT 1.6 liter, modified to work with indirect gas injection.

Table 1: Instrumentation used.

Pre-catalytic lambda sensor	LSU4.9
Passive bench dynamometer	Schenck Type D 360 1E hydraulic
Active bench dynamometer	Antriebstechnik INDY 33/4P
Lambda measurement analyzer	ETAS LA4
Analog input reader	ETAS ES650
Gasoline FLEX ECU	BOSCH MED17ETAS-2.41
Calibration and acquisition software	INCA v7.1
Engine	EA 111 VHT 1.6 liter

Figure 3: EA 111 VHT 1.6 liter engine coupled to the Schenck Type D 360 1E hydraulic Passive bench dynamometer.

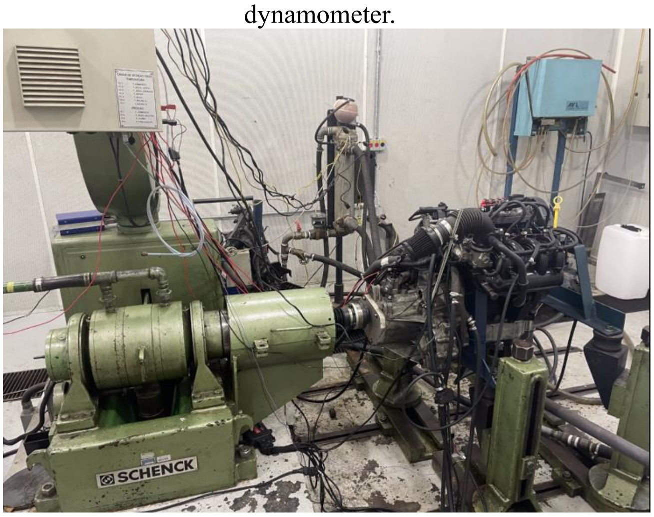


Figure 4: Programmable ECU connected to a data acquisition board.

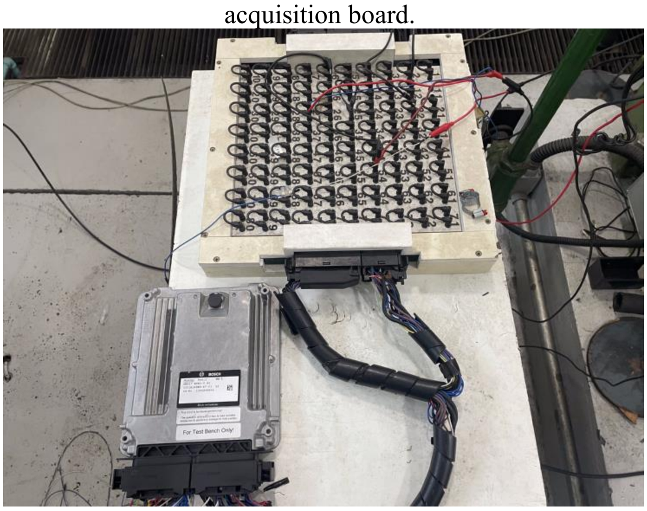


Figure 5: E_CAT software used to control the dynamometer, and INCA software used to control the engine. Both are also used for data acquisition.

RESULTS

There are several methods to estimate the airflow admitted by the engine. One can use a mass airflow sensor (MAF sensor). Another possibility is, by knowing the biogas flow through the injector using instrumentation such as a Coriolis flow meter and knowing the air-fuel ratio through a lambda probe, one can deduce the atmospheric airflow for the tested condition in steady-state. Another possibility is to model the atmospheric airflow for steady-state by having prior knowledge of the characteristic function of the throttle valve used. Only with the use of the diagram illustrated in Figure 2, or with the mass airflow sensor, it is possible to determine the admitted airflow in transient conditions (e.g., varying conditions such as engine speed and intake manifold pressure).

In this research, since there was prior knowledge of the characteristic function of the throttle valve, the airflow model through the throttle valve was used to estimate the volumetric efficiency for different engine speed and intake manifold pressure conditions. The use of biogas, at its stoichiometric air-fuel ratio value, favors volumetric efficiency because less fuel is required for a certain amount of air. The temperature of the biogas line also has an influence as it can result in a lower intake of atmospheric air.

In Figures 6 and 7, the experimentally obtained results are observed. There is a tendency for higher values of volumetric efficiency at high engine speeds and high intake pressure values. The same has been observed for gasoline and ethanol [7]. In Figure 8, the continuous diagram illustrated in Figure 2 was implemented in Simulink. Volumetric efficiency is used in this diagram to model the intake manifold pressure, as seen.

Figure 6: Volumetric efficiency as a function of engine speed and intake pressure. Two-dimensional visualization.

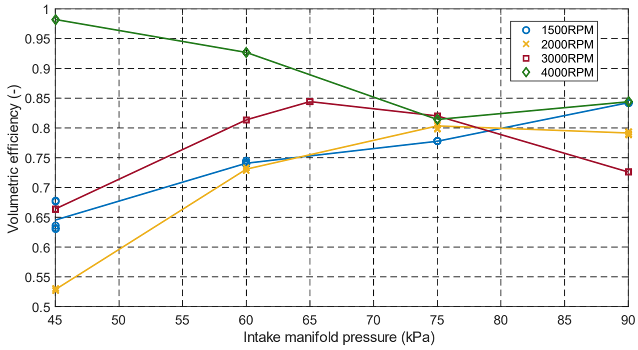
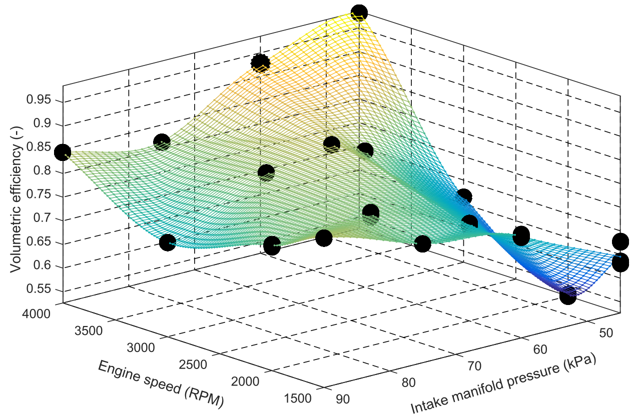


Figure 7: Volumetric efficiency as a function of engine speed and intake pressure. Three-dimensional visualization.



CONCLUSION

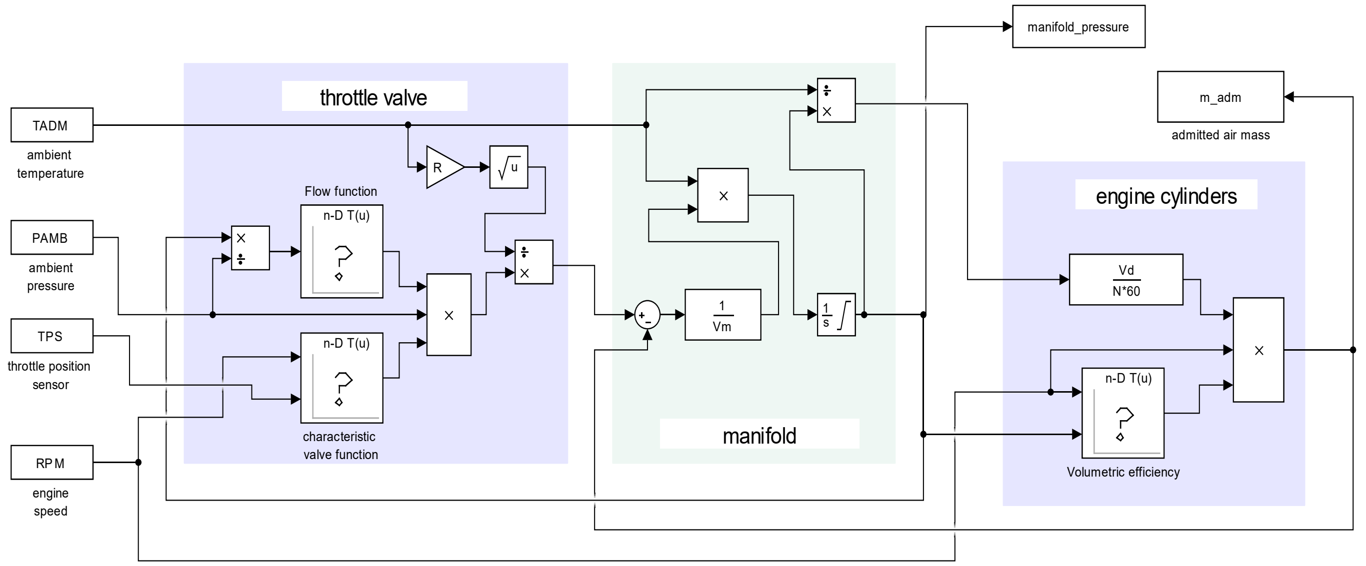
Based on the presented results, it can be concluded that volumetric efficiency is influenced by various factors, such as engine speed, intake pressure, and temperature in the biogas line. It was observed that volumetric efficiency tends to increase as the engine speed and intake pressure are raised.

Furthermore, it was found that volumetric efficiency plays a crucial role in modeling the intake manifold pressure. This demonstrates that understanding and improving volumetric efficiency is essential for the development of efficient control and operation strategies for engines.

Regarding the use of biogas as fuel, the results revealed that less fuel is required for the same amount of air, contributing to improved volumetric efficiency. However, it is important to note that the temperature in the biogas line can have a negative impact on volumetric efficiency. Higher temperatures in this line can impair engine performance and reduce volumetric efficiency. Therefore, proper temperature control measures are necessary to ensure the maximum utilization of this renewable fuel.

In summary, the results of this study emphasize the importance of volumetric efficiency in engine performance and modeling. Engine speed, intake pressure, the use of biogas as fuel, and temperature control in the biogas line are crucial factors to consider in optimizing volumetric efficiency. These findings can provide valuable insights for improving the design and operation of engines, contributing to energy efficiency and sustainability.

Figure 8: Diagram of the continuous air intake model made in Simulink, according to [2].



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