Araştırma / Research

HİDROKSİ GAZ ÜRETİMİNDE YENİ BİR KONTROL TEKNOLOJİSİ

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ÖZ

Bu çalışmanın ana fikri, kullanıcı tanımlı içten yanmalı motor hacmi için optimum bir oksihidrojen üretim algoritması tasarlamaktır. İçten yanmalı motorlarda hidrojen kullanılmasının, belirli bir sınıra kadar performans ve emisyon açısından faydalı olduğu bilimsel olarak kanıtlanmış bir gerçektir. Her ne kadar performans ve emisyonlardaki gelişmeler araştırmacılar tarafından bildirilmiş olsa da; tasarlanan kontrol sistemi, sıkıştırma ateşlemeli motorlarda hidroksi kullanımı için elde edilebilecek en yüksek verime yaklaşma seçeneği sunar. Sistem, HHO üretim oranı ve zenginleştirme miktarının anlık hesaplamaları ve geri bildirim algoritması ile verimliliğin artırılmasını sağlar. Otomatik HHO sistemi, motor bataryalarının ve HHO reaktörlerinin servis ömrünü uzatmak için 0-30 amper aralığında ve nispeten daha düşük çalışma sıcaklıklarında çalışmak üzere tasarlanmıştır.

Anahtar kelimeler: HHO kontrol sistemi, hacimsel verim, hidrojen, motor devri

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ABSTRACT

The main idea of this study is to design an optimum oxyhydrogen production algorithm for user-defined internal combustion engine volume. It is a scientifically proven fact that the use of hydrogen in internal combustion engines is beneficial to performance and emissions until a certain limit. Although improvements in performance and emissions have been reported by researchers; the designed control system offers an option to approach the highest achievable efficiency for hydroxy usage in compression ignition engines. The system allows improving efficiency with instantaneous calculations and feedback algorithm of HHO production rate and enrichment amount. Automated HHO system designed to operate between 0-30 amperes range and relatively less operating temperatures to prolong the service life of engine batteries and HHO generator.

Keywords: HHO control system, volumetric efficiency, hydrogen, engine speed

1. INTRODUCTION

Many years, to bring down the negative effects of fossil fuels on the environment and along with fossil fuel dependency to the lowest levels, researchers focused on alternative energy, and they agreed the idea that hydrogen will play a crucial role in this issue in the near future [1,2,3]. The using of hydrogen as a fuel in internal combustion engines have studied by many researchers. These studies have revealed the many advantages of hydrogen, whereas, relatively fewer disadvantages were expressed by researchers.

Hydrogen has many significant fuel properties. One of the most significant properties of hydrogen is lower heating value, approximately three times higher than conventional liquid fuels. Also high flammability limit, auto ignition temperature, minimum ignition energy, quenching distance and heat of combustion are some

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advantages of hydrogen usage as a fuel solely or fuel enrichment. These advantages improve performance and emission characteristics of diesel and spark ignition engine, except one parameter. Hydrogen usage adversely affects engine volumetric efficiency, due to its too low density. Mentioned by [4], that the negative point of the using hydrogen on the port-injected CI engine is the reduction of volumetric efficiency because the gas fuel will substitute a certain portion of the intake air in terms of volume, which will cause a reduction in the power output. Demonstration of intake air volume occupation by HHO enrichment is presented in figure 1.
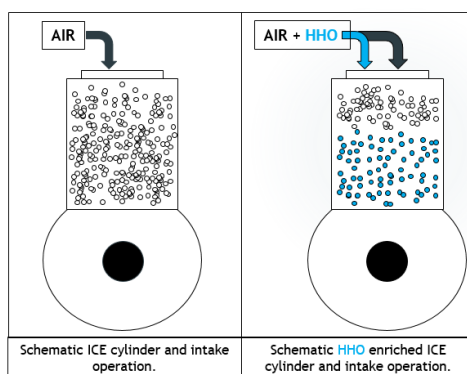

Fig. 1. Demonstration of intake air volume occupation by HHO enrichment

In another study, Ganesh et. al [5], expressed that in the case of lower loads, there is no decrease in volumetric efficiency was observed when the throttle was wide open condition. However, in the case of high loading, the volumetric efficiency considerably reduced because hydrogen occupied more space in the cylinder. Due to decreasing of volumetric efficiency, the cylinder cannot take enough air for combustion when hydrogen using as a fuel enrichment in C.I. engine. Kumar, M. S. et al. reported that in dual fuel operations with hydrogen, it was observed that volumetric efficiency was decreased for all power outputs. The reason for the reduction was that occupying the volume of some of the cylinder by hydrogen which has a lighter density than air [6].

Although hydrogen is considered a high potential fuel for alternative fuel applications, there is still a need to develop some risks in storage, safety, and use. Especially, onboard storage of hydrogen as a main or supplementary fuel might be the greatest challenge for vehicular usage [7,8,9]. Therefore, the usage of HHO obtained by electrolysis is more promising for on-road systems. The using of HHO as fuel enrichment improves performance data, contributing to improved combustion, albeit to a lesser extent, thanks to the extra oxygen in the contents. Having the lowest energy density against highest energy per kilogram brings out some difficulties in storage to reach maximum range for the transportation sector the weight, volume, efficiency, safety of storage as well as the cost of hydrogen is also a problem [10,11,12]. The literature researches show that the usage of hydrogen in internal combustion engines negatively affects volumetric efficiency and thus performance output, especially at low engine revolutions. Yilmaz, A. C. et al. performed their study with a manual circuit is designed to reduce the amount of HHO sent to the cylinders at low revs to prevent reduction of volumetric efficiency with the use of HHO. Peak power output for hydrogen used engines primarily determined by volumetric efficiency, fuel energy density, and pre-ignition [13]. Practical applications showed that these are the limiting factor that determines peak power output. In case of port-fuel injection or premixing of hydrogen with intake air constitutionally, suffer from a loss in volumetric efficiency due to the volume occupied by hydrogen. Hydrogen consists of approximately 30% by volume for the stoichiometric air mixture ratio, whereas the volumetric ratio is approximately 2% for fully-vaporized gasoline [14]. Loss of power density is partially equilibrate by the higher energy content of hydrogen which has the 1,19 times greater stoichiometric heat of combustion per standard kg of air [14,15]. Since the ignition energy of the hydroxy gas is very low, it can be said that there are disadvantages in engine performance and specific fuel consumption at low and medium speeds [13]. On the contrary, these disadvantages may return to advantage at high speeds. In addition, the use of hydrogen as the only fuel in the motors brings with it certain disadvantages that must be overcome, such as recoil, ignition and knocking [16]. For this reason, HHO control should be provided by designing an electronic control card [17]. Furthermore, a control strategy should be developed for the control card to be designed. The aim of the study is to produce HHO that will keep the performance and volumetric efficiency values at an optimum level with an electronic circuit.

2. MULTIPLE FUEL USAGE EFFECTS ON VOLUMETRIC EFFICIENCY FOR C.I AND S.I ENGINES

Manufacturers of commercial vehicles have built their engine designs and improvements on two fossil-based fuels known for many years. The parameters that are desired to be developed as a result of the investigations are two base outputs; performance and emissions. While environmental factors necessitate the improvement of emission values, the user has been desired to improve the performance by the manufacturer. Since both high performance and low emissions with fossil-based fuels are nearly impossible, researchers have turned to alternative fuels and switched to multiple fuels. While high-octane but low-carbon fuels are being tested in petrol engines, biofuels are being tested in the diesel engines where the cetane number is at the forefront.

Despite the fact that the results obtained in the studies seem to improve the emission values, it is seen that the desired performance improvements cannot be achieved due to the low thermal value of the alternative fuels. For this reason, the hydrogen from the newest and cleanest energy carriers has started to be called clean energy in the future, either directly in internal combustion engines or in hybrid uses with fuel cells.

There is a great deal of work nowadays about the use of hydrogen in diesel or gasoline powered engines, with minimal modifications to today's vehicles. One of the important parameters to be considered in these studies is volumetric efficiency.

Table 1. A comparative list of some research on volumetric efficiency by multi-fuel usage

Spark Ignition Engines		
Researcher(s)	**Fuel Mixture**	**Highlights**
Mohammadi, A. et al. [18]	Gasoline + H_2	Hydrogen introduced into the cylinder during intake stroke reduces volumetric efficiency. Thermal efficiency and power output parameters are adversely affected by this reduction.
Karim, G. A. [19]	Gasoline + H_2 + CH_4	Presented two important recommendations on volumetric efficiency in order to make efficient use of hydrogen as a fuel by making some changes to the motor. Variable valve timing technology should be optimized to make better exhaust gas recirculation and increase volumetric efficiency values.
Wang, J. et. al. [4]	Gasoline + H_2 + Natural Gas	In port-injected systems, the power output decreases due to the reduction in volumetric efficiency as gas fuels occupy a certain portion of the inlet air. Despite, while the direct-injection gas engine can solve the volumetric efficiency problem, enabling high power output and low exhaust emissions to be released.
Ganesh, R. H., et. al. [5]	Gasoline + H_2	Volumetric efficiency is adversely affected due to the loss of throttling in gasoline engines except for wide-open throttle condition. It has been observed that when hydrogen is used in the same engine, the volumetric efficiency is high during the operation without the engine load, but when the load is increased, the volumetric efficiency resulting from the displacement of the hydrogen with air is reduced.
Gumus, M. [20]	Gasoline + LPG	The effects of volumetric efficiency changes on the exhaust emission values were investigated by using different levels of LPG usage (25%, 50%, 75% and 100%) in a new generation, closed-loop, multi-point and sequential gas injection spark ignition engine. Although the use of LPG is often implemented with new generation systems in gasoline engines, there is a reduction in engine power output. This reduction depends on the while the passes from the liquid phase to the gas phase, expansion of LPG 230-267 times, thereby reducing the volumetric efficiency.
Çinar, C., et. al. [21]	Gasoline + LPG	single-cylinder gasoline engine modified to run with LPG and have analyzed performance and emission values at variable valve lifts. They pointed out that volumetric efficiency was adversely affected by the use of LPG, resulting in a decrease in performance. The most important problem in using LPG is volumetric efficiency reduction, and they try to improve the volumetric efficiency drop by trying out different valve lift mechanisms.
Karabulut, H., et. al. [22]	Gasoline	the lifted valve period positively affected the cam profile during their studies, while at the same time they emphasizing the decrease in engine performance and volumetric efficiency as the speed, acceleration, and

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		shaking values increased.
Wyszynski,L. P.,et. al. [23]	Unleaded Gasoline + Methanol + Ethanol	Reported about the volatility of different fuels influences the volumetric efficiency change with input charge cooling. Experimental results show that the volumetric efficiency increased by 9% with the transition from port injection to direct injection, and the volumetric efficiency is improved by 3% more with the addition of 10% methanol in the used fuel.
Al-Hasan, M. [24]	Unleaded gasoline + Ethanol	The effects of the performance and emissions on spark-ignited engine of different ethanol-unleaded gasoline mixtures was examined. Initially, it was observed that as the ratio of ethanol in the mixture increases, the volumetric efficiency increases. The reason for this increase is that the temperature of the fuel mixture entering in the cylinder is low due to the ethanol. However, during the experiments, it was observed that the volumetric efficiency dropped from 20% to 25%, although the volumetric efficiency increase when the ethanol percentage of the mixture was between 0% and 20%.
Direct Injection Engines		
Kumar, M. S., et. al., [6]	Diesel + Jatropha oil biodiesel + H_2	The performance impact of using hydrogen fuel at different rates under variable load conditions at nominal speed of 1500 rpm was investigated. In experiments using Jatropha oil biodiesel, high exhaust gas and engine component temperatures, due to increased combustion temperature in standard biodiesel operating conditions, caused a decrease in volumetric efficiency. Hydrogen induction further reduces the volumetric efficiency of all power outputs in the dual fuel process. The reason is that hydrogen occupies a part of the air.
Zhou, J. H., et. al., [25]	Diesel + CH_4 + H_2	Reported that natural gas aspired with air to the inlet side of the air filter to increase the mixing homogeneity of the air and gaseous fuel that is entering the cylinder. So that the air filter also has functioned as a mixing chamber for thoroughly mixing the air-gas-fuel mixture. As a result, it has been reported that there is no need to make any changes to the air inlet system to keep the volumetric efficiency at the same level as normal operation.
Shaaban, S., et. al., [26]	-	This study was conducted about the possible effect of actual turbocharger, non-adiabatic process on engine volumetric efficiency and turbo lag. In addition, it has investigated the increase in compressed air temperature due to thermal energy transfer to the compressor and predicts its effect on motor volumetric efficiency. They mentioned the importance of the negative effect of thermal energy transfer on the volumetric efficiency of the engine.
Saravanan, N., et. al., [27]	Diesel + H_2	Hydrogen enriched air was fed into the cylinder in the intake stroke with the hydrogen flow rate was 20 l / min. As a result, they expressed that the exhaust gas sent to the combustion chamber (EGR technology) must be cooled to increase the volumetric efficiency and thanks to this operation the engine power will be positively affected.
Saravanan, N., et. al., [28]	Diesel + H_2	Two types of fuel supply systems (carburation technique and timed port injection) were used in their work with the diesel engine. Resulting in lower thermal efficiency compared to standard diesel application in the fuel feed with the carburetion technique. it is shown that the continuous 20 l / min hydrogen fuel feed reduces the volumetric efficiency by occupying the air space to be introduced into the cylinder
Köse, H., et. al., [29]	Diesel + H_2	The effects of hydrogen enrichments on a diesel engine performance and emission values were investigated with 2,5H%, 5H%, 7,5H% in volume. The volumetric efficiency and the amount of oxygen in the engine cylinder directly affect the equivalence ratio. Therefore, the results show that 2.5% hydrogen enrichment results in higher volumetric efficiency compared to other enrichment ratios.
Korakianitis, T., et. al., [30]	Diesel + H_2 + Natural Gas + Rapeseed methyl ester	The effects of varying fuels at volumetric efficiency of 750 rpm and 1000 rpm motor speed were investigated. It was reported that the use of hydrogen in dual-fuel operations resulted in a reduction in volumetric efficiency of 2% and 4% for 750 rpm and 1000 rpm respectively. This is due to the fact that the air sent to the cylinder from the intake manifold of hydrogen occupies a certain volume.

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3. METHODOLOGY AND CONTROL STRATEGY

This paper focuses on an algorithm and a new control card designed to optimize volumetric efficiency under full load conditions. The volumetric efficiency (ηv) of an engine is defined as the ratio of the actual air mass flow rate ($\dot{m}_a$) taken to the cylinders divided by the maximum air mass flow rate that could be entered into the cylinder with respect to the engine geometry. It can be written as;

$$\eta v = \frac{\dot{m}_a}{\dot{m}_{th}} \tag{1}$$

Where; $\dot{m}_a$ is actual mass flow rate of air through the engine and the $\dot{m}_{th}$ is maximum possible mass flow rate of air according to engine geometry.

The flow chart of the control unit is presented in figure 2. First, the volume information of the engine is entered by the user. Secondly, the engine speed information from the sensor is compared with the designed electronic control card and the speed level is determined by the appropriate control strategy. Finally, the low, medium or high current is drawn from the battery according to the determined revolutions per minute (rpm).
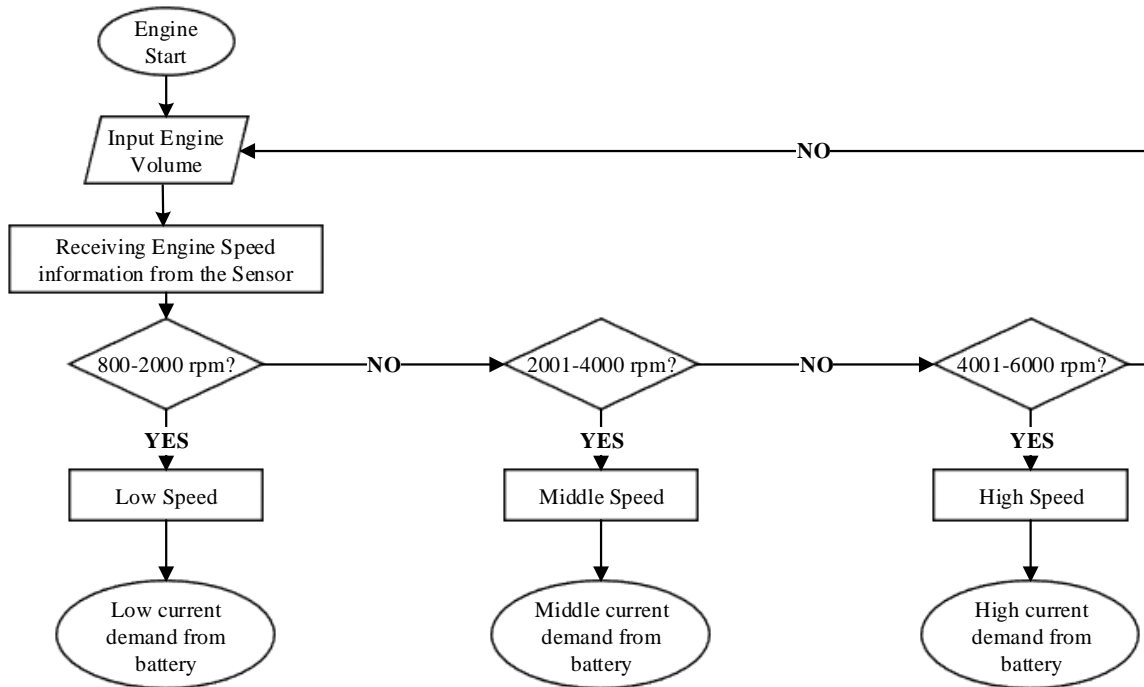

Fig. 2. Flow chart of the designed electronic control unit

Fig. 3 shows the structure of the control mechanism created in MATLAB / Simulink. Volumetric efficiency calculations based on volume information that the driver enters into the system. Then the engine divided into three subgroups according to the number of revolutions. The idle operating speed of a standard commercial engine is more than 800 rpm [31]. Therefore, the flow rate reduced to avoid overburdening the HHO, which has slow start times at low speeds (range of 0-800 rpm) [13]. The designed electronic control unit intended to reduce the HHO flow by adjusting the voltage and current values. The three different volumetric efficiency ranges for this are 800-2000 rpm / 2001-4000 rpm / 4001-6000 rpm. Each range has a minimum critical volumetric efficiency value. These have been determined as 70%, 80% and 90% respectively [13,32,33]. The designed control unit automatically controls the amount of HHO production by adjusting the current drawn from the engine battery so that the volumetric efficiency does not reduce under a certain limit at any rpm intervals.

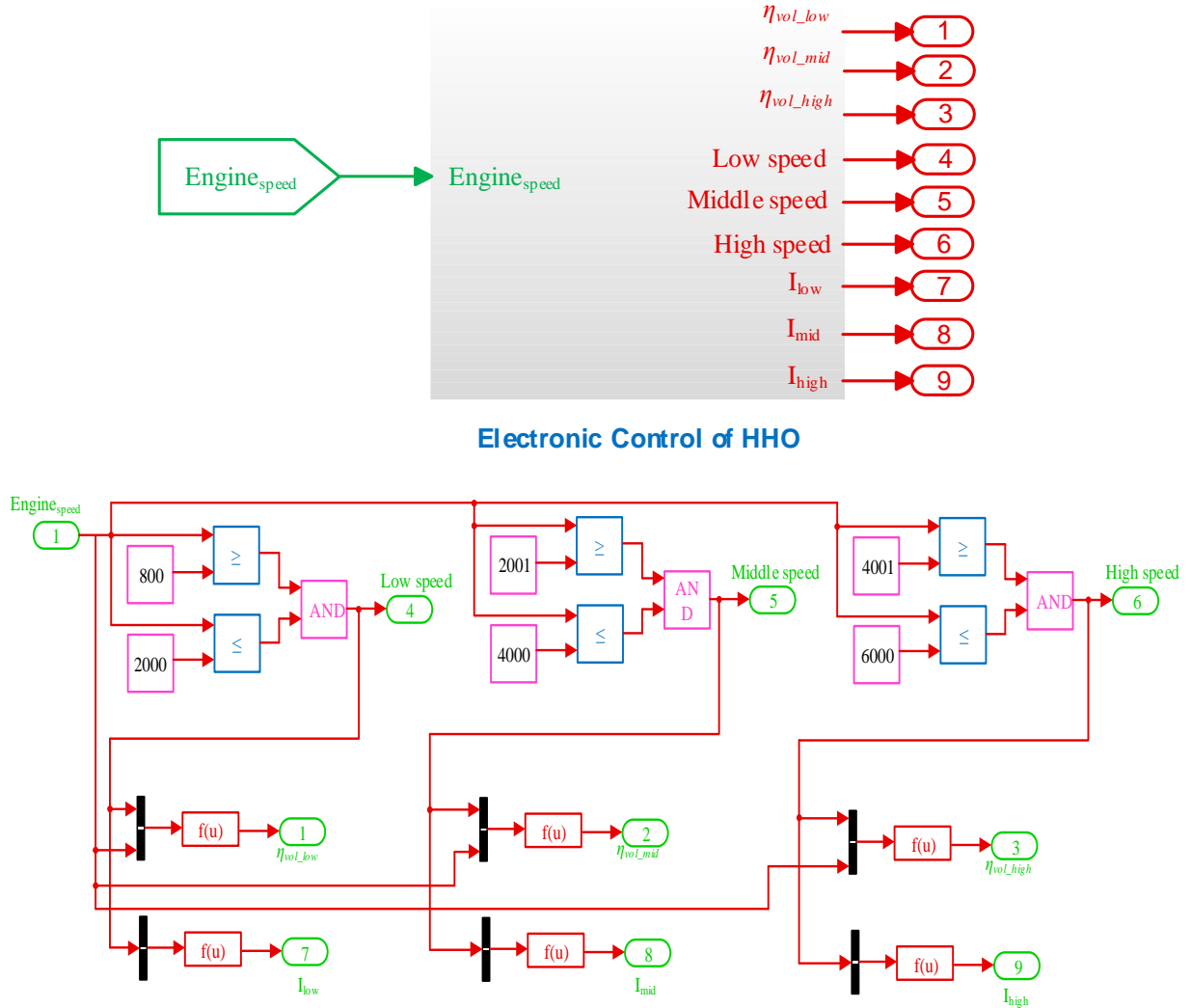*A NEW CONTROL TECHNOLOGY IN HYDROXY GAS PRODUCTION*

Fig. 3. The structure of the generated electronic control mechanism

Pulse width modulation (PWM), the most common speed control method, is used to control HHO production [17,34,35,36]. PWM changes the signals at the range of 0-5 Volts with the help of a Metal Oxide Semiconductor Field Effect Transistor (MOSFET). After the value of the current to be drawn from the battery is determined, the PWM draws the desired current from the battery by generating pulses in a determined period. PWM circuits output a square waveform with a varying on to off ratio. The average ratio range vary from 0 - 100 %. This ratio between "on-time" and "total-time" is called as duty cycle, which is expressed in percentage [37]. Techinical strategy of this research is to obtain variable HHO production by producing different duty cycles with respect to digital signals from the speed sensor. As a result, thanks to the control strategy developed, the speed information from the motor and the volume information from the drive has been revealed the effect of volumetric efficiency on the current drawn from the battery.

4. RESULTS AND DISCUSSION

It is known that the amount of air taken into the cylinders during HHO enrichment is reduced and the oxygen required for complete combustion could not be taken in the cylinders. Especially at low engine speeds, when

HHO enrichment is kept in constant flow rate, the amount of oxygen decreases in the cylinders due to the light density of the hydrogen. Therefore, both performance and emission values are adversely affected. The designed model controls the HHO production by changing the electrolysis current according to the changing engine speeds. Designed to optimize the volumetric efficiency problem, especially at low and middle engine speed ranges, this card determines the volumetric efficiency ratio by calculating the maximum amount of theoretical air that can be taken into cylinders for each engine speeds. After all received data, it provides sending the variable current to the electrolyzers according to engine speeds intervals to ensure that the HHO production quantity is maintained at the defined level, 70%, 80% and 90%, for the specified engine speed ranges (low, mid, and high speeds) as it is presented by 3-D graph, in figure 4. In this way, it improves engine performance and emissions at optimum levels even at low engine speeds.
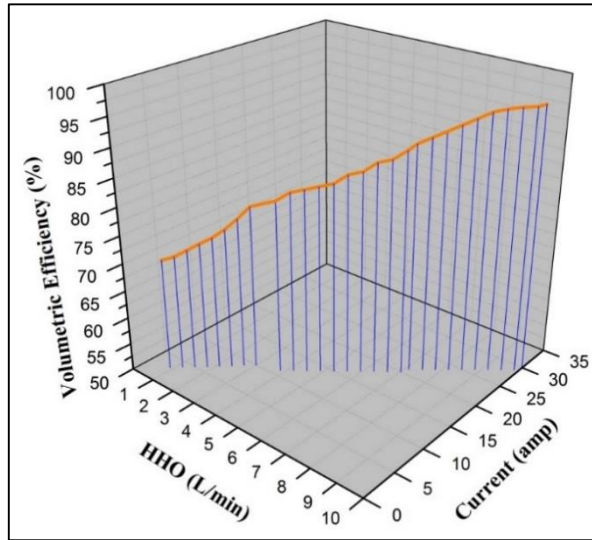

Fig. 4. HHO production rates vs current drawn to optimize volumetric efficiency

The amount of HHO produced by electrolysis is limited by the capacity of the reactors. [31] was conducted the experiments with HHO gas obtained from electrolysis. As they reported in their study, when electrolyzers reached maximum capacity, the increasing of water electrolysis amount almost stop and after this point overcurrent could not be increased more HHO gas flow (Fig. 5.). Direct current applications without PWM signals, 50% of load power consumes 71% of full power that 50% of power goes to the load (HHO generators/dry cell) and the remaining 21% is dissipates as heat [37].
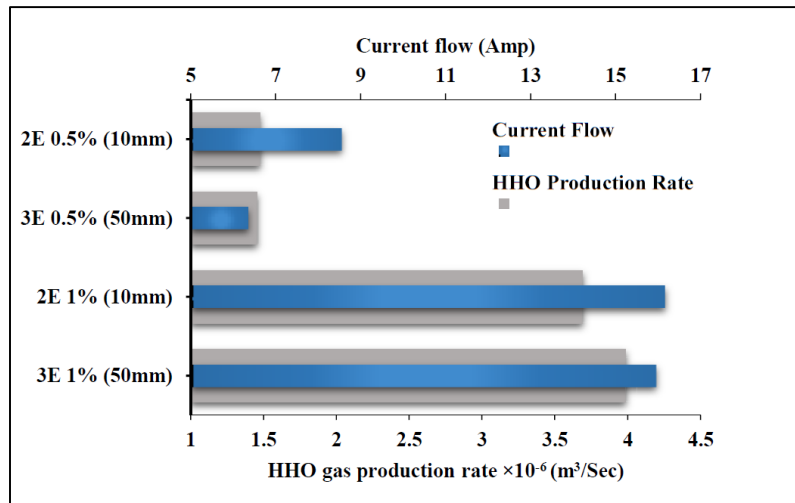

Fig. 5. Current flowrate versus average HHO production rate [31]

Furthermore, the lifetime of the reactors can be extended by arranging optimum current flow drawn by the

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HHO system. Therefore, the maximum current delivered to the reactors, as shown in Figure 4, is limited to 30 amperes which is produce 10 liter per minute HHO gas.

An illustrative example:

During the engine volumetric efficiency (Eq.1) calculation, it is assumed that the actual amount of air is equal to the theoretical amount of air and determined by multiplying engine shaft speed with total engine displacement volume. Under normal conditions actual mass flow rate less than theoretical mass flow rate of the air. [38] presented a Eq. (2) for calculating the maximum air mass flow rate that could be taken into a cylinder.

$$\dot{m}_{th} = \frac{\rho_a * V_d * N}{2 * 60} \qquad (kg/s) \qquad (2)$$

Where;

ρ_a: Density of air (~1,225 kg/m^3 @ normal conditions)
V_d: Displacement volume of the Cylinder
N : Engine Speed (rpm)

when the Eq. (1) and Eq. (2) are combined, the volumetric efficiency could be written as;

$$\eta v = \frac{2 * 60 * \dot{m}_a}{\rho_a * V_d * N} \qquad (3)$$

If Eq. (2) is considered for 1.6 L (1600cc) ICE @ 1500 rpm, calculation results with 0,025 kg/s air which is equal to 1212 L/min intake air for ICEs. If the amount of produced HHO is considered as 10L/min instead of 2L/min without the control system, then 0,66 % reduction comes out on volumetric efficiency. Additionally, results of this study provide power saving by preventing unnecessary current drawn from engine battery. 1500 rpm was selected in the calculations because the common issue is volumetric efficiency reductions and knocking problems at low engine speeds in the literature [13, 36]. As it is mentioned in the methodology previously, 1500 rpm is a value at the defined low-speed engine range. So it is an explanatory choice to present changes in most dangerous working zone of a ICEs with HHO enrichment.

5. CONCLUSIONS

It has been determined that the adaptation of the HHO system to the operating principles of internal combustion engines is highly necessary in terms of total energy efficiency and it is aimed to be solved by this study. For this purpose, a control unit was designed to control the amount of HHO production automatically by adjusting the current drawn from the engine's battery so that the stable volumetric efficiency could be sustained at any determined engine speed ranges.The continuous constant volumetric flow rate of produced hydrogen as HHO and variable mass airflow rate related to engine speed has provided without degrading the volumetric efficiency, thus can lead better combustion. Amount of necessary HHO can be produced interdependent to the low, medium and high engine speeds by the aid of designed HHO control system that is designed to control with the current automatically. HHO control system is designed in MATLAB/ Simulink. The flow chart and the structure of the generated electronic control mechanism are presented with figures. A descriptive numerical example has been included to the end of results and discussion section to better understand the system's gain.

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