AI-ASSISTED ECU PROGRAMMING FOR TWINING INJECTORS SUPPLYING FLEXIBLE SYNGAS-BIOGAS-HYDROGEN BLEND TO ENGINES

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Abstract - The engine utilizing a flexible variable blend of syngas-biogas-hydrogen fuel requires fuel supply via a dual-injector system controlled by a specially designed ECU. The control law for the injectors in the dual-injector system can be described by two piecewise linear functions: the first injector's opening increases linearly, then is held constant; the second injector begins to open when the syngas concentration in the mixture exceeds 50%, and then increases linearly. Artificial Intelligence (AI) can be employed to program the complex control operation of the dual-injector system based on the provided hardware specifications and the injector opening rule. The adaptability of the ECU to the fuel mixture composition and the engine operating regime can be simulated using the Proteus software. This allows us to save a significant amount of time and effort in ECU testing before manufacturing.

Key words - Renewable fuel; Flexible fuel; Hydrogen; ECU; Dual-injector system

1. Introduction

The trend of energy transition has become a top priority for the international community to address climate change and mitigate greenhouse gas (GHG) emissions. According to the 2015 Paris Agreement, to limit the global temperature increase to well below 2°C, and ideally to 1.5°C above pre-industrial levels [1], nations must achieve net-zero or net - negative CO_2 emissions by around the middle of the 21st century [2, 3]. Due to the direct correlation between atmospheric temperature and cumulative CO_2 concentration, establishing a roadmap towards net zero has become an urgent task for most countries [2, 4, 5, 6].

Strategies to achieve this goal focus on the comprehensive transformation of the energy system, including: significantly reducing the use of fossil fuels, enhancing energy efficiency, promoting electrification in end-use energy sectors, and strictly controlling carbon emissions [7 - 9]. This transition process must be balanced with sustainable development goals [10, 11] and the financial capacity to replace the existing fossil fuel infrastructure [12]. However, the reality indicates that no single renewable energy source can completely replace fossil fuel energy, making the combination of diverse renewable energy sources the most viable option.

Vietnam affirmed its strong commitment to the fight against climate change at COP26, targeting net-zero emissions by 2050 through the implementation of the Paris Agreement mechanisms [13]. This strategy is clearly articulated in the recently adjusted Power Development Plan VIII (PDP VIII), where renewable energy is projected to constitute a significant share of the national energy mix in the coming decades. With a favorable geographical position in the tropics, Vietnam possesses abundant resources of solar, wind, and biomass energy.

However, the fundamental limitation of renewable energy sources is their intermittency, with power output fluctuating daily or changing irregularly based on weather and climatic conditions. To overcome this issue and ensure the reliability of the energy supply system, the solution of integrating various renewable energy sources, known as a Hybrid Renewable Energy System (HRES), which has been proposed and implemented [15 - 19].

Recent studies have demonstrated significant improvements in combustion quality with the addition of hydrogen to biogas [20 - 22]. Utilizing a biogas-hydrogen mixture allows for operation at a lower optimal equivalence ratio compared to neat biogas, leading to a reduction in CO and HC emissions. However, it must be noted that increasing the hydrogen fraction tends to increase NOx emissions due to higher combustion temperatures [20]. Furthermore, when the biogas composition changes under the same operating conditions and hydrogen ratio, the fuel supply strategy must be adjusted accordingly [22 - 24].

The components in the syngas-biogas-hydrogen mixture have highly distinct combustion properties. Hydrogen is notable for having the highest laminar flame speed, approximately 3.2 m/s, and can combust over a wide equivalence ratio range from 0.8 to 3.2, whereas methane has a laminar flame speed of only about 0.25 m/s and a narrow flammability range from 0.8 to 1.2. For syngas, a mixture of 95% CO-5% H_2 has a maximum laminar flame speed of approximately 60 cm/s, while a 50% H2-50% CO mixture achieves a higher speed of about 190 cm/s. Another crucial characteristic is that as the hydrogen content in the mixture with biogas and syngas increases, the optimal spark timing tends to decrease.

For stationary engines operating at near-constant speed, the ignition system is typically designed with a fixed optimal spark timing suitable for a specific fuel type and rated speed mode. However, when transitioning to the use of a syngas-biogas-hydrogen fuel mixture with a wide range of compositional variations, both the spark timing and the fuel delivery rate must be flexibly adjusted to maintain optimal performance. In the context of an engine running on a flexible syngas-biogas-hydrogen fuel mixture within an HRES, the precise control of the fuel supply process and the ignition timing becomes critically important to ensure optimal operating parameters. Traditional carburetion systems and mechanical ignition cannot meet such flexible adjustment requirements. Therefore, this study focuses on developing an Electronic Control Unit (ECU) to manage the fuel injection timing and spark timing for an engine utilizing syngas-biogas-hydrogen with varying compositions.

The ECU, specially designed for this application, uses an Arduino Mega microcontroller, receiving input signals including load mode, speed mode, and the proportions of biogas and hydrogen in the mixture with syngas. It then outputs the ignition control signal and the control signal for the dual injector system. Traditionally, programming the control logic for implementation in the ECU is a complex process, demanding significant time and effort. Recent advances in Artificial Intelligence (AI) have created new opportunities to simplify and accelerate ECU development, particularly in engine control [25 - 26]. This study presents the application of AI to aid in the programming of the ECU that controls the dual injector system and ignition system of the flexible gaseous fuel engine, thereby contributing to reducing development time and enhancing the accuracy of the control algorithm.

2. Simulation of the Engine Control System using Proteus

In this study, we utilize a Honda GX200 engine for computational simulation. The engine has a cylinder bore of 68 mm, a piston stroke of 54 mm, and a compression ratio of 8.5. The engine generates a maximum power output of 4.8 kW at 3600 rpm when fueled with gasoline. The lower heating values of the fuels are: CH_4 (33.906 MJ/m^3), H_2 (10.246 MJ/m^3), and CO (12.035 MJ/m^3). Based on the fuel mixture composition, we can calculate the fuel-to-air ratio using the equivalence ratio as well as the energy variation supplied by the fuel for each engine cycle. The complete combustion of 1 mole of CH_4 requires 2 moles of oxygen, whereas the complete combustion of 1 mole of H_2 or 1 mole of CO only requires 0.5 moles of oxygen. Consequently, when the content of H_2 or CO in the mixture increases, the amount of air supplied to the cylinder decreases.

The simulation of an ECU for an engine in Proteus using the Arduino microcontroller provides a comprehensive and flexible approach to designing and testing engine control systems. Leveraging the virtual environment of Proteus, one can create a detailed model of the ECU, integrating virtual sensors, actuators, and the Arduino microcontroller to replicate the behavior of a real engine. This enables the simulation of various engine operating conditions, such as changes in temperature, pressure, and speed, while allowing for the testing of control algorithms and strategies in a safe and cost-effective environment. The Arduino microcontroller can be programmed to process sensor data, make decisions, and control actuators like fuel injectors and ignition coils, ultimately aiming to optimize engine performance, fuel efficiency, and emissions. Overall, simulating the engine ECU in Proteus using Arduino offers a powerful tool for the development, testing, and optimization of engine control systems, helping engineers create engines that are more efficient, reliable, and environmentally friendly.

3. Results and Discussion

3.1. Control Strategy for Dual Injector System

The maximum injection duration (calculated in crank angle degrees) is determined such that when the engine operates at full load and rated speed, the equivalence ratio of the fuel-air mixture reaches the stoichiometric value ϕ=1 (theoretical complete combustion). Furthermore, the end of the injection must be timed to ensure that, by the end of the intake stroke, all fuel injected into the intake runner is completely drawn into the engine to prevent backfire. To satisfy these conditions, when the engine operates at a power output of Pe=5 kW and a rated speed of n=3600 rpm, the multi-component gaseous fuel mixture can be injected into the engine's intake runner at a pressure of p=1 bar through a dual injector system with a nozzle orifice diameter of d=6 mm. When the injection pressure and engine rated speed are constant, the nozzle orifice diameter is proportional to $\sqrt{Pe}$. When the injection pressure and engine power output are constant, the nozzle orifice diameter is proportional to $\sqrt{n}$. When the engine power output and rated speed are constant, the nozzle orifice diameter is proportional to $1/\sqrt[4]{p}$. Figure 1 shows the maximum injection duration diagram for the case where the engine is running on a multi-component gaseous fuel mixture, with a power output of 5 kW, a rated speed of 3600 rpm, and a pressure of 1 bar, using the dual injector system with a 6 mm nozzle orifice diameter. The diagram defines how the opening durations of the first injector (VP1) and the second injector (VP2) are coordinated to ensure a stable fuel supply over a wide range of fuel compositions. This control strategy is essential for engines operating in hybrid renewable energy systems, where fuel composition can vary significantly with biomass quality and operating conditions.

In this diagram, the syngas volumetric concentration is shown on the horizontal axis. The maximum injection duration of each injector, expressed in crankshaft angle degrees, is shown on the vertical axis. Injector VP1 operates over the entire range of fuel compositions and serves as the primary fuel delivery device. As the syngas concentration increases, the opening duration of VP1 increases linearly to compensate for changes in the lower heating value and combustion characteristics of the fuel mixture. Injector VP2 is activated only when the syngas concentration exceeds a threshold of 50%. Once activated, the opening duration of VP2 increases linearly with syngas concentration, enabling a smooth transition from biogas-dominant fueling to syngas-dominant operation.

The coordinated operation of VP1 and VP2 results in a gradual redistribution of fuel delivery rather than abrupt changes in injection behavior. This smooth transition is particularly beneficial for engine performance, as it minimizes transient disturbances in air–fuel ratio and combustion stability. The piecewise linear characteristics defined by points P1–P5 provide a simple yet effective rule for distributing fuel between the two injectors, ensuring adequate fuel delivery while avoiding backfire and maintaining proper mixture formation.

The diagram consists of 4 straight segments with the following landmark coordinates:

- P1(0, t_0), where t_0 is the maximum injection duration when only VP1 supplies a fuel mixture without syngas, and VP2 is inactive.

- P3(100, t_{100}), where t_{100} is the maximum injection duration when both injectors VP1 and VP2 collectively supply syngas to the engine. In this case, the fuel contains 100% syngas, and both VP1 and VP2 are active.

- The coordinates of the remaining milestones are: P2(60, j_{100}), P4(50, 0), and P5 (0,0).

During operation, the maximum injection duration of VP1 follows the line P1P2P3, while the maximum injection duration of VP2 follows the line P5P4P3.

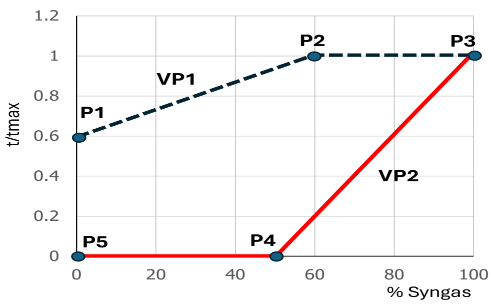


***Figure 1.** The opening duration of injectors VP1 and VP2 in the dual-injector system as a function of the syngas concentration in the syngas-biogas-hydrogen fuel mixture (Honda GX200 Engine)*

3.2. Simulation of the ECU for Dual Injector Control within Proteus

3.2.1. AI Programming

When programming the Arduino microcontroller using the traditional method, we are required to write individual commands according to the established flowchart. With the assistance of AI, we only need to convey to the machine the principle of control, the hardware components, and the characteristics of the pulses we need to generate to control the ignition system and the fuel injectors.

The AI-assisted programming procedure is structured to reflect the logical sequence of a four-stroke engine cycle and the corresponding control actions of the ECU. Before presenting the detailed implementation, the overall workflow is summarized as follows:

(i) generation of a virtual crankshaft position signal (TDC pulses),

(ii) determination of ignition timing based on engine speed (TDC pulses)

(iii) generation of coordinated injection pulses for the dual-injector system according to engine load and fuel composition.

The following are the steps for microcontroller programming with the assistance of AI Claude 4.5 Sonnet

Objective of programmation:

I aim to develop a project in Proteus simulating the fuel injection system of a 4-stroke spark ignition engine powered by renewable fuel blends (Syngas, Biogas, Hydrogen). Please provide Arduino code to implement this system based on the specifications below.

Principle of Operation:

• Each flywheel rotation generates one **Top Dead Center** (TDC) pulse.

• A full engine cycle consists of **two crankshaft rotations**, thus, two TDC pulses, separating **intake-compression phase** and **combustion-expansion-exhaust phase**.

• The **intake-compression phase** duration is longer than the **combustion-expansion-exhaust phase**, thus, there are **alternating long and short intervals** between consecutive TDC pulses.

• Two injectors **INJ1** and **INJ2** are used to supply fuel mixture to the engine.

• The **Ignition pulse** (IGN) and **Injection** pulses **(INJ1, INJ2)** occur once per engine cycle during the **longer TDC interval**.

• The **IGN pulse timing** advances (occurs earlier) as the engine speed (rpm) increases.

• The **pulse widths** of INJ1 and INJ2 pulses depend on the load and on the fuel components in the mixture.

• The engine speed **decreases with an increase in load and increases with a decrease in load**.

Hardware Requirements:

• **Arduino Mega** (referred to MC).

• **LCD 20x4** with I2C interface (address 0x3F).

• **Serial Monitor** set at 115200 baud rate.

• **Potentiometer1** connected to PIN A0 of MC, providing Rate_rpm values ranging from 500 to 4000.

• **Potentiometer2** connected to PIN A1 of MC, providing Load values ranging from 0 to 100.

• **Potentiometer3** connected to PIN A2 of MC, providing Biogas values ranging from 0 to 100.

• **Potentiometer4** connected to PIN A3 of MC, providing Hydrogen values ranging from 0 to 100.

• **Potentiometer5** connected to PIN A4 of MC, providing Syngas values ranging from 0 to 100

Project Implementation Steps:

This project consists of 3 steps:

• **Step 1:** Generate the Top Dead Center (TDC) pulse.

• **Step 2:** Generate the Ignition (IGN) pulse.

• **Step 3:** Generate the Injection pulses (INJ1 and INJ2).

Step 1: Simulate the Top Dead Center (TDC) Pulse Generation

• Read Rate_rpm value at A0.

• Engine cycle period: Engine_period = 60,000,000*2 / Rate_rpm (in microseconds).

• During an Engine_period there are two TDC pulses: the first pulse of the current engine cycle occurs at time ti, the second pulse of the current engine cycle occurs at time tj.

• The first pulse of the next engine cycle occurs at time tk.

• tj - ti = 0.45 * Engine_period (short interval of TDC pulse).

• tk-tj=0.55 * Engine_period (long interval of TDC pulse).

• Pulse width: TDC_PulseWidth=200 microseconds.

• Pulse output PIN: Digital pin D45 of arduino MC.

• Use TimerFive library to generate precise TDC pulses

Step 2: Simulate the Ignition (IGN) Pulse Generation

• IGN pulse specifications:

- IGN_delay=(5000-Rate_rpm)/10 (us).
- Pulse OUTPUT PIN: D10.
- For each Engine_period, there is only one IGN pulse occurring during the long interval of TDC pulse.
- Concretely, let ti, tj, and tk be the appearance timings of 3 consecutive TDC pulses, if tk-tj<tj-ti then: Generate IGN pulse with IGN_PulseWidth=250 (us), starting at time tk+0.40* Engine_period + IGN_delay (us).
- Use TimerOne to control IGN pulse.

Step 3: Simulate the Injection Pulses Generation (INJ1 and INJ2).

- **INJ1 and INJ2 pulses specifications:**

• The pulse widths of INJ1 and INJ2 are proportional to the load but inversely proportional to biogas or hydrogen.

• The current engine speed (real_rpm) decreases with increase in Load, but it increases with decrease in Load (it is referred to external load).

- **Calculation:**

• Read Load value at PIN A1.

• Read Biogas, Hydrogen, Syngas at PIN A2, A3 and A4, respectively.

• Calculate: Bio_conc=Biogas/(Biogas+Hydrogen+Syngas)*100

• Hydro_conc=Hydrogen/(Biogas+Hydrogen+Syngas)*100

• Syn_conc=Syngas/(Biogas+Hydrogen+Syngas)*100

• Calculate INJ1_PulseWidth=Load*20+Syn_conc*10 (us).

• Calculate INJ2_PulseWidth=Load*20-(Bio_conc*5+Hydro_conc*3) (us).

- **Creation injection pulses:**

• For each Engine_perriod, there is only one INJ1 pulse and one INJ2 pulse occurring during the long interval of TDC pulse, the same as IGN pulse.

• Concretely let ti, tj, and tk be the appearance timings of 3 consecutive TDC pulses, if tk-tj<tj-ti then: Generate INJ1 pulse at pin D3 of Arduino MC, starting at time tk+0.1* Engine_period (us), with pulse width INJ1_PulseWidth; Generate INJ2 pulse at pin D4 of Arduino MC, starting at time tk+0.15* Engine_period (us), with pulse width INJ2_PulseWidth.

• Use TimerThree to control INJ1 pulse, TimerFour to control IN2 pulse.

- **Display on the LCD:**

If abs(Rate_rpm-PreviousRate_rpm)>5 then display:

▪ Line 0: Display "Speed", Rate_rpm value.

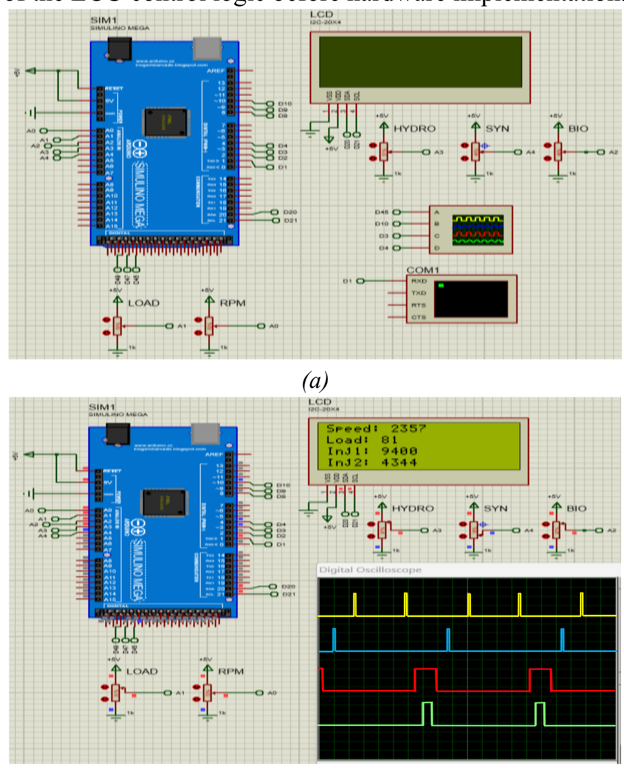
▪ Line 1: Display “Load”, Load value.

▪ Line 2: Display “Inject”, Int(INJ_PulseWidth).

PreviousRate_rpm=Rate_rpm.

3.2.2. Results

Figure 2 presents the Proteus-based simulation framework used to evaluate the proposed ECU control strategy. The diagram demonstrates how the Arduino-based ECU integrates input signals representing engine speed, load, and fuel composition, and generates corresponding control signals for ignition timing and the dual-injector system. This simulation environment plays a critical role in validating the adaptability and correctness of the ECU control logic before hardware implementation.



(a)

(b)

Figure 2. *ECU simulation diagram in Proteus (a) and the simulation results for a typical case (b)*

Figure 2a presents the ECU simulation diagram in Proteus. The diagram includes an Arduino Mega microcontroller and a 4-line LCD screen for display. The engine operating regime is represented by the speed sensor and the load sensor, connected to pins A0 and A1, respectively. The fuel composition sensors for Biogas, Hydrogen, and Syngas are connected sequentially to Arduino pins A2, A3, and A4. The crank angle position signal is fed into pin D45. The output signals for controlling the ignition, the first injector (VP1), and the second injector (VP2) are outputted sequentially from pins D10, D3, and D4. The input and output signals are displayed on the virtual oscilloscope, and the pulse values are exported via the virtual COM1 port. The LCD screen displays the values for engine speed, load mode, and the opening duration of injectors VP1 and VP2. The microcontroller is loaded with the program written by the AI mentioned above. Figure 2b presents the typical results for a case where n = 2357 rpm and 81% load. The fuel composition was randomly selected. The program yields the opening durations of the first and second injectors as 9400 µs and 4344 µs, respectively. These results demonstrate that the proposed ECU is capable of generating distinct and coordinated injection pulses for the two injectors under a given operating condition. From a system perspective, this confirms that the dual-injector strategy can dynamically redistribute fuel delivery according to engine load and fuel composition. In a hybrid renewable energy system, such adaptability is critical because the gaseous fuel supplied to the engine may fluctuate depending on biomass availability and gasification conditions. The observed injector responses indicate that stable engine operation can be maintained without manual recalibration of the fuel system.

The data exported via the virtual COM1 port can be saved to plot the variation of the pulses. Figure 3 illustrates the crankshaft rotation angle pulse, the ignition pulse, the control pulse for injector VP1, and the control pulse for injector VP2. These pulses correspond to the pulses displayed on the oscilloscope in the respective operating mode.

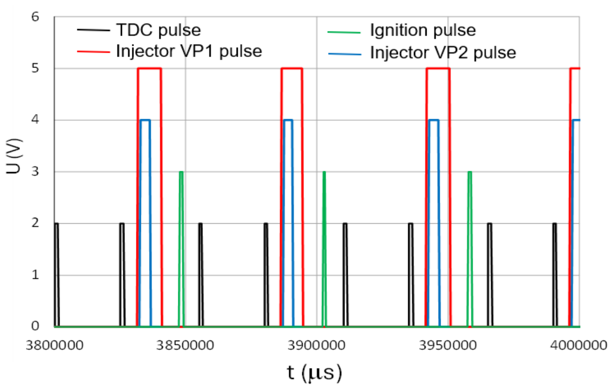


Figure 3. *Pulses received at the virtual COM1 port*

Figure 4 illustrates the variation of the injection time signal with respect to the syngas concentration in the mixture with biogas and hydrogen. The engine speed is held constant at n = 2357 rpm, and the engine load mode is kept unchanged at 81%. The syngas concentration is varied at 50%, 60%, and 80%.

According to the diagram in Figure 4, the results show that the injection times of VP1 are 10015 µs, 11816 µs, and 13384 µs, corresponding to syngas concentrations of 50%, 60%, and 80% in the fuel mixture. Respectively, within this range of variation, the injection time of VP2 remains nearly constant, while the injection time of VP1 increases with the syngas concentration in the fuel mixture. This behavior reflects the control strategy in which VP1 plays the dominant role in compensating for variations in fuel composition. From an engine performance perspective, this adaptive increase in injection duration helps maintain the required fuel energy input despite changes in the lower heating value and combustion characteristics of the fuel mixture.

In the context of an HRES, where syngas composition may vary due to changes in gasifier operating conditions, this result confirms that the proposed ECU can automatically adjust fuel delivery to preserve stable power output and combustion stability.

Figure 5 illustrates the variation of the opening duration of injectors VP1 and VP2 under random changes in speed, engine load mode, and fuel composition. We can observe that the system exhibits high adaptability to the random changes in the engine operating conditions and the supplied fuel mixture composition. For HRES, such robustness is essential, as engines are often subjected to unpredictable load demands and fuel quality fluctuations. The ability of the ECU to respond smoothly to these variations reduces the risk of misfiring, backfire, or efficiency loss during transient operation.

The simulation results confirm that the proposed AI-assisted ECU and dual-injector strategy provide effective adaptability to variations in fuel composition and engine operating conditions. By adjusting injection durations in response to syngas concentration, load, and speed, the system ensures a consistent fuel energy supply to the engine. This capability directly supports reliable engine operation within hybrid renewable energy systems, where fuel variability is unavoidable. The results, therefore, highlight the practical relevance of the proposed control approach for renewable-fuel-based power generation.

From these simulation research results, we can proceed to fabricate the ECU to supply the flexible variable blend of syngas-biogas-hydrogen fuel to the engine operating within an HRES.

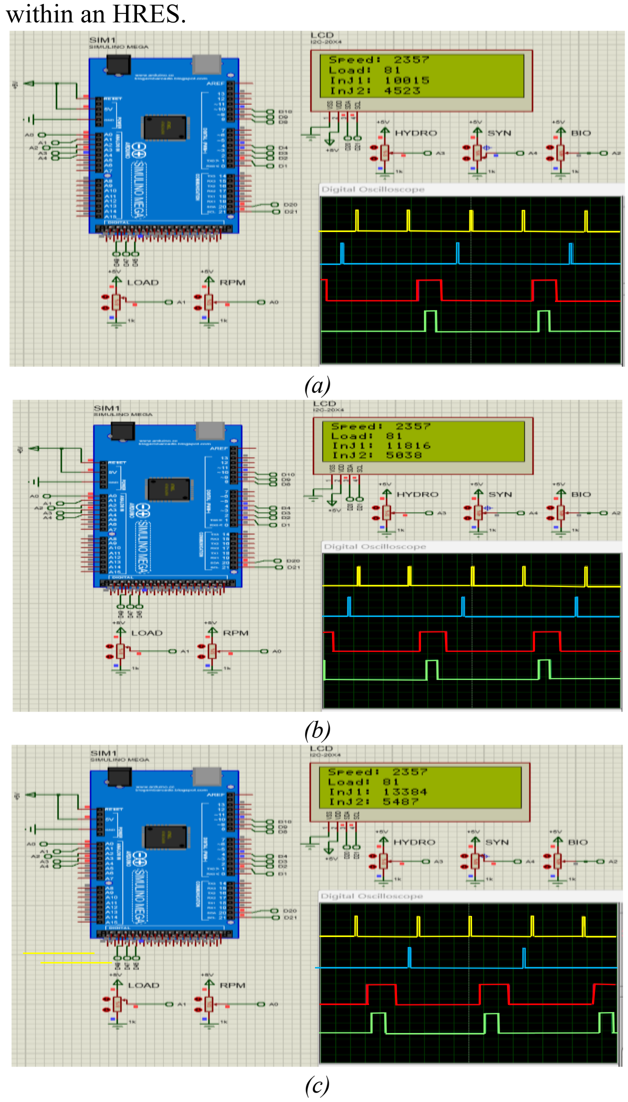


Figure 4. *Change in injection duration with respect to the fuel mixture composition*

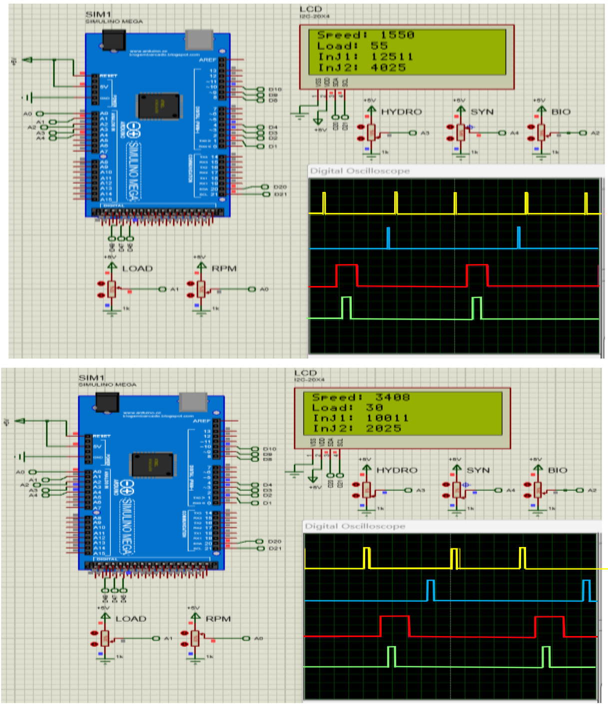


Figure 5. *Variation of injection time with respect to speed, engine load mode, and fuel composition*

4. Conclusion

Based on the research results presented above, the following conclusions can be drawn:

- The dual-injector system, which coordinates the operation of two injectors controlled by a specially designed ECU, is capable of supplying a flexible variable blend of syngas-biogas-hydrogen fuel to the engine operating within a HRES.

- The control law for the injectors in the dual-injector system can be described by two piecewise linear functions: the first injector's opening increases linearly, then is held constant; the second injector begins to open when the syngas concentration in the mixture exceeds 50%, and then increases linearly.

- Proteus is an effective tool for simulating the ECU that controls the process of supplying the variable composition fuel mixture via the dual-injector system according to the engine operating regime.

- AI assists us in microcontroller programming to control the complex operation of the dual-injector system, based on the provision of hardware specifications and the injector opening rule.

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