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Effect of internal and external EGR on cyclic variability and emissions of a spark ignition two-stroke cycle gasoline engine

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ABSTRACT

Conventional two-stroke cycle engine suffers from typical drawbacks including lower combustion efficiency and excessive emissions of uHC and CO which are largely due to low in-cylinder average charge temperature at low load and speed regions of engine operating conditions. Utilising the hot burned Exhaust Gas Recirculation (EGR) technique can boost the in-cylinder average charge temperature of the engine. The influence of hot burned gases applied by means of both Internal EGR and External EGR strategies on the combustion stability and exhaust gas emission of a single-cylinder two-stroke cycle engine running at low-load and mid-load of operating conditions was investigated experimentally along with simulation works using 1-D engine simulation code. The results indicated that both In-EGR and Ex-EGR improved the combustion stability (lower misfire cycle) and decreased the concentrations of uHC and CO emissions, specifically at low speed region; however, NOx concentration was increased. At Internal EGR setting of 30%, the Coefficient of Variation for maximum in-cylinder pressure (COV_{Pmax}) reached the minimum by 5.64 while when External EGR percentage was 25%, COV_{Pmax} approached about 6.67 at the mid-speed (2000 rpm) of engine operating condition.

Keywords: Two-Stroke cycle engine; Internal EGR; External EGR; Cyclic Variability; Exhaust gas emissions.

INTRODUCTION

Concerns on sustainable energy supply and environmental protection are exerting rigorous demands on modern internal combustion engines (ICEs) to improve fuel efficiency. There is also a need to reduce carbon dioxide (CO_2) emissions to reduce global warming, and this calls for improvement in the design of ICEs [1-3]. Two-stroke cycle engines are well known for their significant advantages involving components, simple construction, lightweight, and less costly to manufacture. Two-stroke engines also have the potential to deliver almost twice the power density since there is one power stroke per revolution of the crank. The combination of lightweight and twice the power density makes two-stroke cycle engines feature a significant power-to-weight ratio and offer this advantage over the four-stroke engines [4-8]. For a long time, the objective of the different research works on two-stroke cycle engines optimisation was to eliminate two typical drawbacks consisting high emissions of uHC and poor fuel efficiency. The former leads to unstable engine operation (cycle-to-cycle variation) combined with incomplete combustion, especially at idle and light engine loads. The latter is fuel short circuit at medium and full engine loads [9-15]. However, due to the short-circuiting of the fuel before combustion, this has resulted in deterioration in the engine's overall performances, especially poor combustion efficiency and high white smoke emission problem [16-22]. This cyclic variation is associated with lower average charge temperature of the cylinder; i.e., at low speed and load since the energy per each combustion cycle is too low to sustain high temperature for the next combustion cycle without misfiring occurrence. In-cylinder gas temperature at exhaust port closure moment (T_{epc}) can be increased sufficiently with the employment of exhaust hot burned gases; such a way is known as exhaust gas recirculation (EGR) technique [23-29]. The amount of T_{epc} must be high to achieve a complete combustion at the end of the compression stroke by means of spark plug ignition [30-36]. Basically, the major effects of EGR utilisation can be defined as: Charge-Heating Effect, Dilution Effect, Heat Capacity Effect and Chemical Effect [37-43]. Combustion burned gases inside of the combustion chamber can be retained in the combustion chamber by means of exhaust port area restriction. This strategy of burned gas utilisation is known as internal EGR (In-EGR). Likewise, a fraction of exhaust gas leaving the exhaust can be brought and rerouted back into the engine intake by also using a valve and this technique is called external-EGR or Ex-EGR [44-47]. This study aims to investigate the influence of both In-EGR and Ex-EGR on the combustion stability (cyclic variability) and exhaust emissions of a spark ignition single-cylinder two-stroke cycle engine by means of a 1-D simulation code along with experimental works.

METHODS AND MATERIALS

Experimental Set-Up and Instrumentation

A single cylinder two-stroke, naturally aspirated and liquid-cooled engine was used in conjunction with a comprehensive test bed facility for the experimental work. The reference for the engine specification is given in Table 1. The schematic view of the experimental set-up is presented in Figure 1, which illustrates the engine-dynamometer, the In-EGR and Ex-EGR mechanisms and the other instrumentations. Here, the In-EGR and Ex-EGR mechanisms are shown, which are basically valves placed after the exhaust outlet and are manually controlled. A gate type valve (diameter 25mm) fitted onto the EGR line adjusted the quantity of the exhaust gas to be rerouted back into the engine intake. The EGR line was insulated to minimise the heat losses to the environment. The valve and the feedback line are called Ex-EGR strategy of this engine set-up. Right after the exit of the exhaust port, there is a ball-type valve (38 mm diameter) designated as In-EGR strategies. This valve regulated the outgoing hot burned gases so that a small fraction of residual combustion gases remained in the cylinder at the end of the exhaust stroke and mixed with the incoming cylinder charge.

Table1. Experimental engine specifications.

Engine Type	Single Cylinder 2-Stroke
Bore × Stroke	59 x 54.5 (mm)
Displacement	149 (cm^3)
Scavenging Type	Loop Scavenging
Scavenging Timing	117.5 CAD a/bTDC
Exhaust Timing	82.5 CAD a/bTDC
Exhaust System	Expansion Chamber
Compression Ratio	8.5:1
Cooling System	Liquid Cooled
Fuel Supply System	Port Fuel Injection

Table 2. Engine operating conditions in simulation at idle and low speeds.

Parameters	Ranges
Speed [rpm]	1000/1500/2000
Fuel [-]	Gasoline 95
In-EGR [%]	0/5/15/30
Ex-EGR [%]	0/5/10/25
IMEP [Bar]	1
AFR [-]	14

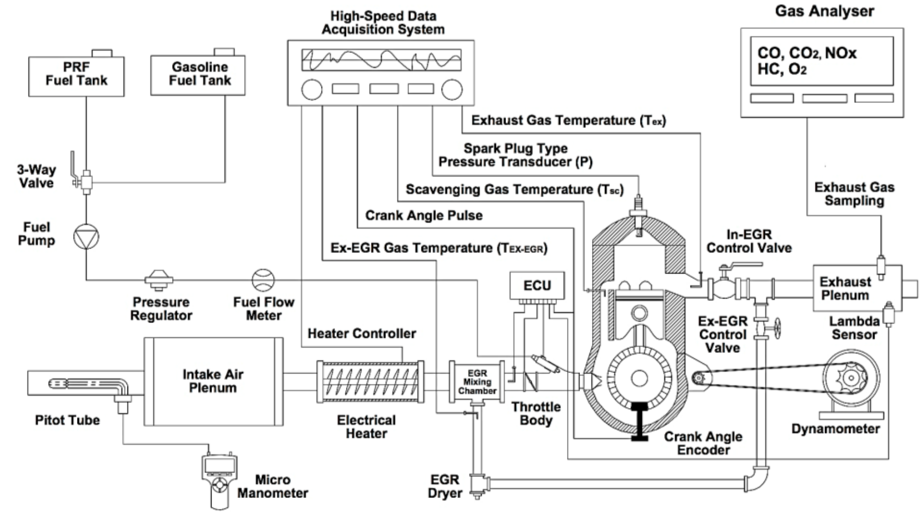


Figure 1. Schematic view of experimental set-up.

Engine Simulation

The reference engine was modelled using a 1-D engine simulation code wherein the emission was using the engine's geometrical inputs such as intake and exhaust runner, piping modelling, detailed specifications of combustion chamber and cylinder head shape, exhaust, and intake port timing. The graphical representation of the engine is as shown in Figure 2. The graphical 1-D code simulated representation for the engine is illustrated in Figure 2 based on the operating condition variables as presented in Table 2. In order to calculate the scavenging efficiency to estimate the percentage of In-EGR and Ex-EGR, it was presumed that scavenging process followed the idealised Isothermal Perfect-Mixing model [48-51]. Through the simulation procedures, engine was run in conjunction with different percentages of In-EGR and Ex-EGR in order to examine the combustion stability and the engine exhaust emissions output. Subsequently, three engine speeds were considered including 1000, 1500, and 2000 rpm representing idling speed, low-speed and mid-speed engine operating conditions, respectively. Afterwards, the improvements in combustion stability and exhaust gas emissions due to utilisation of both In-EGR and Ex-EGR are presented in next two sections, which include the simulation and experimental results.

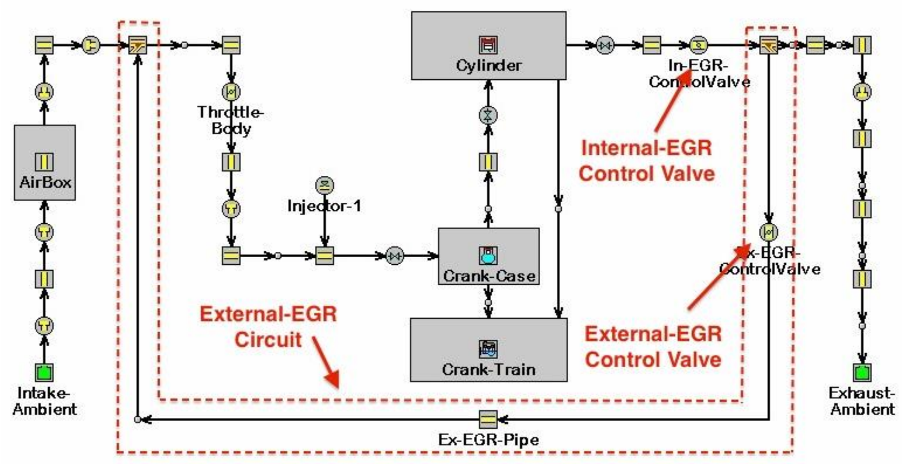


Figure 2. Engine 1-D simulation representation.

RESULTS AND DISCUSSION

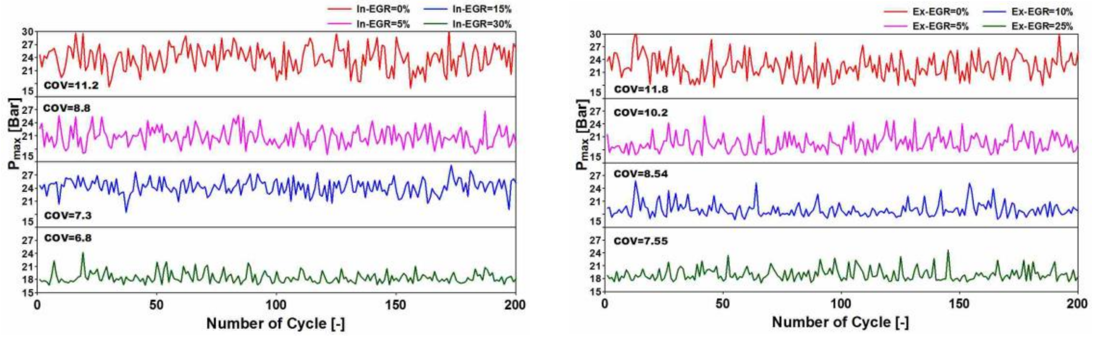
Combustion Stability at Idling, Low and Mid-Speed

In order to determine the behaviour of the engine's combustion stability, maximum in-cylinder pressure (P_{max}) as pressure-related parameters was taken into consideration while the In-EGR and Ex-EGR rates were varied. This was performed for 200 consecutive engine cycles. For each of the test point, the coefficient of variation of P_{max} (i.e. COV_{Pmax}) was calculated to evaluate the engine combustion stability (cyclic variability) trend. Table 3 represents the engine operating condition at the designated engine speeds showing the setting preference for the In-EGR and Ext-EGR performed in experimental works.

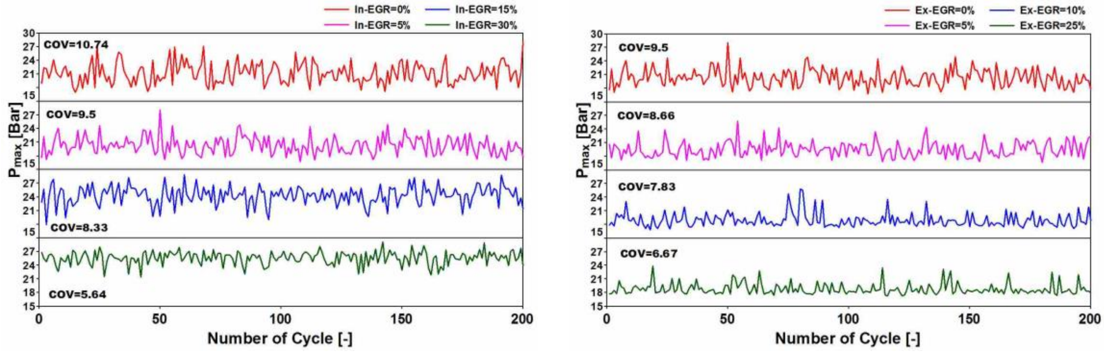
Table 3. Engine operating conditions in experimental at idle, low and mid speeds.

Speed [rpm]	In-EGR [%]	Ex-EGR [%]
1000	20	12
1500	14	7
2000	10	4

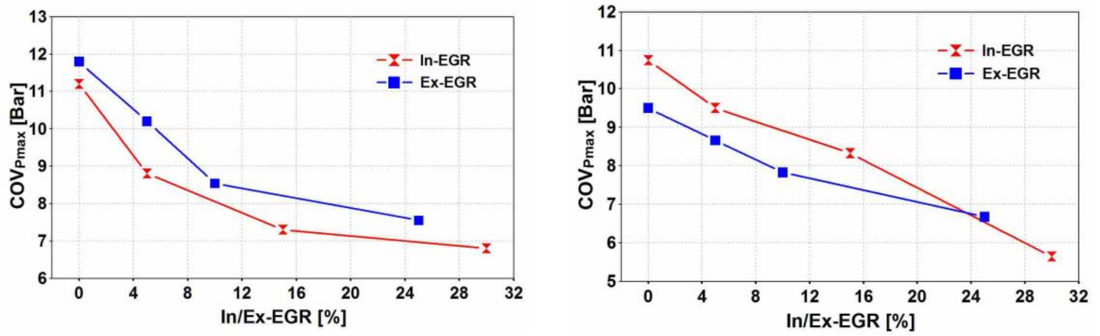
Figure 3(a) illustrates the influence of In-EGR on the cyclic variability of P_{max} when the engine was at the idle speed of 1000 rpm. Here, COV_{Pmax} decreased when the percentage of In-EGR was increased. The fluctuation of P_{max} will be finally suppressed when In-EGR was at 30% setting, i.e. COV_{Pmax} of 6.8. Figure 3(b) shows the influence of Ex-EGR on the cyclic variation of P_{max} at 1000 rpm. When the opening of the Ex-EGR was increased, cyclic variation of P_{max} reduced. The fluctuation of P_{max} was controlled when the Ex-EGR setting was 25% and COV_{Pmax} was 7.55. The overall effect of both In-EGR and Ex-EGR on the cycle-to-cycle variation of P_{max} at idle-speed is explained in Figure 3(e). The higher the In/Ex-EGR percentage applied, the lower the cyclic variability of P_{max}. The curves in the figure imply that in general when the In-EGR is applied, the cyclic variation of P_{max} is lower than that of the Ex-EGR. As for Figure 3(c), the influence of In-EGR utilisation on cyclic variation of P_{max}, at mid-speed (2000 rpm) is shown. Table 2 shows the parameter settings employed for this simulation test.



(a). COV_{Pmax} vs. In-EGR at 1000 rpm **(b)**. COV_{Pmax} vs. Ex-EGR at 1000 rpm



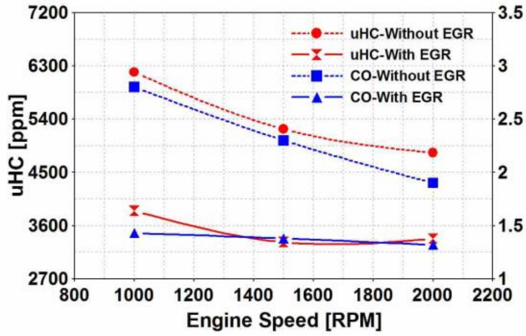
(c). COV_{Pmax} vs. In-EGR at 2000 rpm **(d)**. COV_{Pmax} vs. Ex-EGR at 2000 rpm



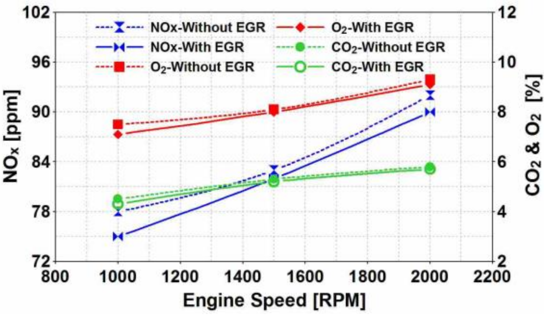
(e). COV_{Pmax} variations at 1000 rpm **(f)**. COV_{Pmax} variations at 2000 rpm

Figure 3. Influence of In/Ex-EGR on COV_{Pmax} at Idling and low speed in simulation

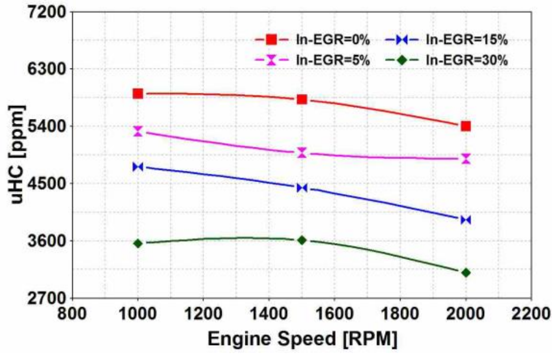
When the concentration of In-EGR was increased, the cyclic variation of P_{max} was noted to improve. At In-EGR setting of 30%, the COV_{Pmax} has reached the minimum by 5.64. Similarly, the influence of Ex-EGR on the engine cyclic variation of P_{max} is illustrated in Figure 3(d). The pattern of the curves proved that the utilisation of Ex-EGR decreased the magnitude of COV_{Pmax} and this indicated that the cyclic variation of P_{max} has improved. As for Figure 3(f), the variation of COV_{Pmax} due to In-EGR and Ex-EGR is presented. In general, it can be deduced that the higher the concentration of Ex-EGR, the lower the cyclic variation of P_{max}. Consequently, it was conceived that the cyclic variability was more likely to be influenced by variation of In-EGR rather than Ex-EGR when the engine was run at the idling speed, while the Ex-EGR was more prominent at mid-speed region.



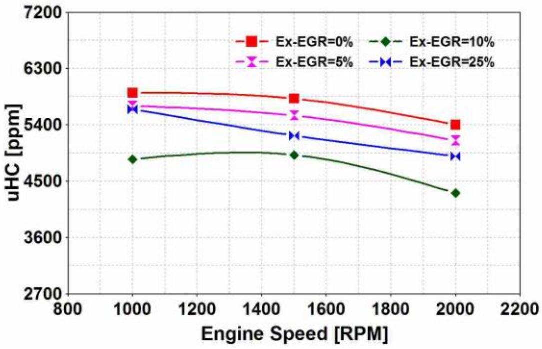
(a). uHC and CO vs. EGR (experimental)



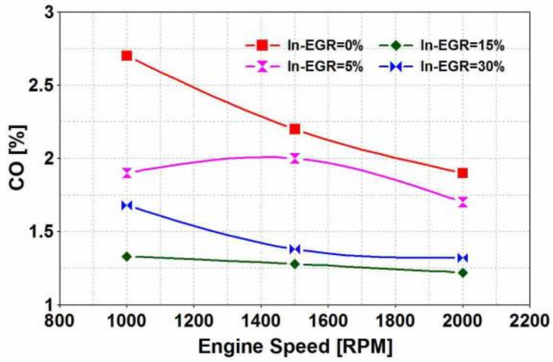
(b). NOx, CO_2, O_2 vs. EGR (experimental)



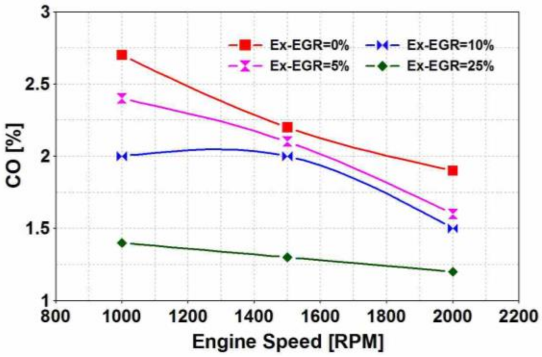
(c). uHC vs. In-EGR (simulation)



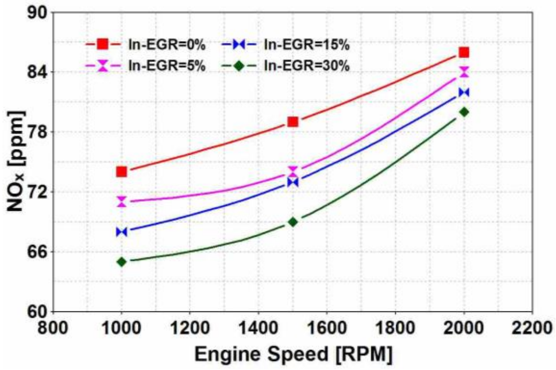
(d). uHC vs. Ex-EGR (simulation)



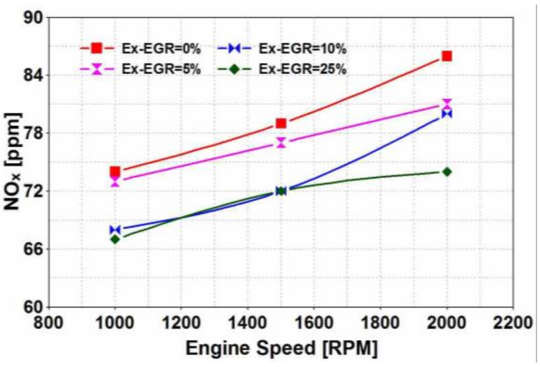
(e). CO vs. In-EGR (simulation)



(f). CO vs. Ex-EGR (simulation)



(g). NOx vs. In-EGR (simulation)



(h). NOx vs. Ex-EGR (simulation)

Figure 4. Influence of In/Ex-EGR on emissions at idling and low/mid-speed conditions.

Emissions Variations at Idling, Low and Mid-Speed

In order to examine the exhaust gas emissions of the engine due to the variation of In/Ex-EGR rates, the engine was run on 1-D engine simulation code at the three engine speeds as mentioned in Table 2. Figure 4 represents the overall operating condition of the engine in the simulation works regarding several concentrations of In-EGR and Ex-EGR for exhaust gas emissions analysis. Meanwhile, the variation in concentration of uHC, CO, NOx, CO_2, and O_2 emissions in relation to In-EGR and Ex-EGR changes at experimental results are illustrated in Figure 4(a) and Figure 4(b) respectively. As for the experimental work, the exhaust gas concentrations were assessed under two separate conditions. First was without EGR and second was with EGR application as explained in Table 3. Once the incomplete combustion cycles (i.e. misfire cycle) were eliminated by using In/Ex-EGR, the exhaust constituents such as uHC and CO were altered. Figure 4(a) illustrates that the concentration of these constituents significantly decreased at all speeds. However, the improvements in NOx, CO_2, and O_2 concentration were observed to be slight as shown in Figure 4(b). Moreover, in the simulation works, the variation in concentration of uHC in relation to In-EGR and Ex-EGR changes is illustrated in Figure 4(c) and Figure 4(d), respectively. As a whole, both In-EGR and Ex-EGR improved uHC emission output of the engine regardless of the engine speed. As the percentage of both In-EGR and Ex-EGR was increased, the concentration of uHC decreased accordingly. The higher the percentage of the In/Ex-EGR, the lower is the uHC emission. Comparing the curves of the figure, it can be concluded that the concentration of uHC emission was more influenced by In-EGR rather than Ex-EGR.

The concentration of CO emission in conjunction with In-EGR and Ex-EGR varied with respect to the three speeds as illustrated in Figure 4(e) and Figure 4(f), respectively. As can be seen in the figures, the concentration of CO emission decreased when the percentage of both In-EGR and Ex-EGR was increased. In general, it can be deduced that the CO emission has the same sensitivity to the variation of both In-EGR and Ex-EGR. The trend depicted by the curves in both figures proved that the emission of CO was less sensitive to the variation of both In-EGR and Ex-EGR when the engine speed was at 2000 rpm (mid-speed) because the curves were converged at 2000 rpm while they were diverged at 1000 rpm. In Figure 4(g) and Figure 4(h), the influence of both In-EGR and Ex-EGR on the concentration of NOx emission is demonstrated. respectively. In general, the utilisation of both In-EGR and Ex-EGR decreased the NOx emission accordingly. The rate of NOx reduction in the case of In- EGR application followed a regular pattern; however, the rate of NOx reduction in the case of Ex-EGR did not, meaning that when the percentage of Ex-EGR was increased from 10 to 25, the concentration of NOx did not decrease considerably, in particular at 1000 rpm and 1500 rpm. Furthermore, the NOx reduction at Ex-EGR setting of 5% was more remarkable when the speed was at 2000 rpm. It is worth noting that even though uHC and CO were decreased (as the speed was increased), the concentration of NOx was raised when the engine speed increased. As such, it can be said that higher NOx concentration is attributed to higher combustion temperature developed in the combustion chamber.

CONCLUSIONS

A simulation and experimental investigation were conducted on a spark ignition single cylinder two-stroke cycle engine operated at constant load and three different speeds. Cyclic variability and emission characteristics of the engine were investigated in accordance with the variations of In-EGR and Ex-EGR. It was deduced that the emission characteristics of the engine in terms of uHC, CO, NOx, CO_2 and O_2 and also the engine combustion cyclic variability were strongly influenced by In/Ex-EGR rates. In general, the results can be summarised as follows:

- Experimental results are in a good agreement with those of the simulation work wherein it can be deduced that the In/Ex-EGR regulated the engine emissions as well as its combustion variability.
- Both In-EGR and Ex-EGR mitigated uHC and CO emission quite remarkably but at the expense of NOx concentration having to be increased which was attributed to higher combustion temperature developed in the combustion chamber.
- The cyclic variability was more likely to be influenced by variation of In-EGR rather than Ex-EGR when the engine was run at idling speed, while the Ex-EGR was more prominent at the mid-speed region.
- The concentration of uHC emission was more influenced by In-EGR rather than Ex-EGR.
- The emission of CO was less sensitive to the variation of both In-EGR and Ex-EGR when the engine speed was at 2000 rpm (mid-speed).

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