International Journal of Automotive Technology, Vol. 3, No. 1, pp. 41−46 (2002)

1229−9138/2002/007−06

COMPARISON OF HYDROCARBON REDUCTION IN A SI ENGINE BETWEEN CONTINUOUS AND SYNCHRONIZED SECONDARY AIR INJECTIONS

H. S. Sim and S. H. Chung*

School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Korea

(Received 3 November 2001)

ABSTRACT−Effect of secondary air injection (SAI) on hydrocarbon reduction has been investigated in a single cylinder SI engine operating at cold-steady/cold-start conditions. The hydrocarbon emission and exhaust gas temperature with and without catalytic converter were compared with continuous and synchronized SAIs, which injected secondary air intermittently into exhaust port. Effects of SAI location, SAI pressure, SAI timing, and location of catalytic converter have been investigated and the results are compared for both SAIs with base condition. At cold-steady condition, the rate of HC reduction increased as the location of SAI was closer to the exhaust valve for both synchronized and continuous SAIs. The emission of HC decreased with increasing exhaust-A/F when it was rich, and was relatively insensitive when it was lean. The timing of SAI in synchronized SAI had significant effect on HC reduction and exhaust gas temperature and the synchronized SAI was found to be more effective in HC reduction and exhaust gas temperature compared to the continuous SAI. At cold-start condition, when the catalytic converter was located 20 cm downstream from the exhaust port exit, the catalytic converter warm-up period for both SAIs decreased by about 50%, and the accumulated hydrocarbon emission during the first 120 s decreased about by 56% and 22% with the synchronized and continuous SAIs, respectively, compared to that of the base condition.

KEY WORDS : Secondary air injection (SAI), Synchronized SAI, Continuous SAI, Hydrocarbon, SI engine

NOMENCLATURE

$(A/F)_{eng}$: air-fuel ratio before secondary air injection
$(A/F)_{exh}$: air-fuel ratio after secondary air injection
l : downstream distance from exhaust port exit
l_{sai} : location of secondary air injection
l_{temp} : location of temperature measurement
SAI : secondary air injection
t_{ig} : timing of spark ignition
t_{sai} : timing of synchronized secondary air injection

1. INTRODUCTION

Emission standards become stringent for unburned hydrocarbons (UHC) from automobiles. Since significant portion of HC is emitted during cold-start when catalyst is not warmed up, it is important to reduce engine-out HC together with decreasing catalyst warm-up duration during cold-start. Various techniques have been proposed to reduce HC emissions (Kim *et al*., 2001). Close coupled catalyst and electrically heated catalyst have been adopted to shorten catalyst warm-up duration. Secondary air injection (SAI) and exhaust gas ignition (Ma *et al*., 1992) have been tested to reduce engine-out HC and also to accelerate catalyst heating. Advantages of SAI include HC reduction through oxidation and the acceleration of catalyst warm-up by the exothermic energy from the oxidation of HC, CO, and H_2. Furthermore, catalyst light-off temperature, defined as the temperature with 50% HC conversion, can be decreased through the increase in oxygen concentration. With *continuous* SAI into the exhaust pipe (Kollmann and Zahn, 1994), HC emissions were reduced by 32% when a three-way catalyst was not used. It has also been demonstrated that HC emissions were significantly reduced during the first 70 s in the FTP test with engine air-fuel ratio before SAI, $(A/F)_{eng} = 8.2$ and air-fuel ratio after SAI, $(A/F)_{exh} = 14.5$ (Crane *et al*., 1997). These studies with continuous SAI showed that the reduction rate of engine-out HC was about 30% at idle condition without having a three-way catalyst. This relatively low reduction rate with continuous SAI may be due to inefficient use of secondary air. Since exhaust valve is opened only about a quarter of a cycle, a large portion of secondary air injected during the exhaust valve

**Corresponding author.* e-mail: shchung@snu.ac.kr

closed period may not be utilized effectively.

In order to utilize injected air effectively, a *synchronized* SAI (Sim *et al.*, 2000, 2001) has been proposed to improve HC reduction, in which the secondary air is injected through a solenoid valve at certain specified timing and duration. Improved mixing of engine-out exhaust gas and secondary air could lead to further reduction in engine-out HC and to increase in exhaust gas temperature. Higher exhaust gas temperature will then assist the catalyst light-off process during cold-start.

In the present study, the performance of continuous and synchronized SAIs were investigated with the focus on the effect of parameters including SAI location, $(A/F)_{exh}$, SAI timing, and SAI pressures. Also, HC reduction rate and catalytic converter temperature at cold-start were compared with the continuous SAI and the synchronized SAI.

2. EXPERIMENT

The experimental apparatus consisted of a single cylinder SI engine, an engine control unit, a dynamometer, a secondary air injection system, and an exhaust gas analyzer. The engine specification is listed in Table 1.

The engine control unit together with a PC acquired test data and adjusted engine parameters such as spark timing (t_{ig}), fuel injection timing and duration, and synchronized SAI timing (t_{sai}) and duration. Figure 1 shows the schematic of exhaust system with SAI. Exhaust HC was monitored with a FID analyzer at the sampling location of 2 m downstream from the exhaust port exit. Exhaust gas A/F was measured by a wide-range oxygen sensor at a location of 1.8 m downstream from the exhaust port exit in order to avoid unintentional heating of exhaust gas by the sensor, which was operated at 800°C. Exhaust gas and catalytic converter temperatures were measured by K-type thermocouples at various locations. Secondary air for the synchronized SAI was injected through a gas injector into the two exhaust ports using a Y-branched nozzle. Three injection locations

Table 1. Test engine specifications.

Type	Single cylinder, DOHC
Bore x Stroke	82 × 93.5 (mm)
Displacement volume	494 (cc)
Compression ratio	10.3
Fuel	Gasoline
Valve timing (CA)	
Intake Open	BBDC 8°
Close	ABDC 40°
Exhaust Open	BBDC 50°
Close	ATDC 10°

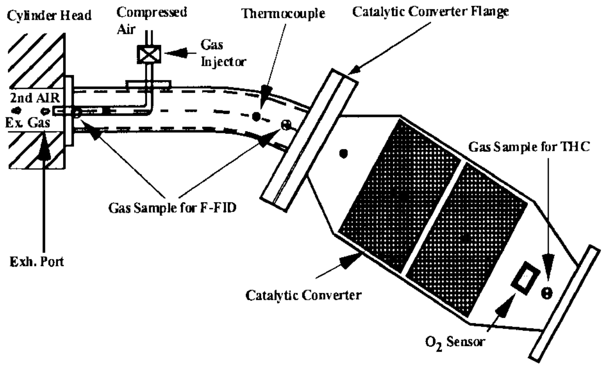

Figure 1. Schematic of exhaust system with secondary air injection.

were tested; l_{sai} = 0 cm, –2.5 cm and –5 cm, where l indicates the distance downstream from the exhaust port exit. The delay time between injector driving signal and actual air injection was found to be 3 ms, which was compensated in data representation.

To simulate cold-start, the engine was operated at 1200 rpm with the coolant temperature of 20°C. Unless otherwise specified, the engine was at idle state with $(A/F)_{eng}$ = 10, the spark ignition timing of t_{ig} = 10°CA BTDC, and the exhaust-A/F after SAI of $(A/F)_{exh}$ = 14.5.

The $(A/F)_{exh}$ for the synchronized SAI was controlled by air injection duration at an air pressure of 400 kPa, while for the continuous SAI it was regulated by the air injection pressure, which was below 120 kPa. At cold-steady condition, the base condition for the comparison with continuous and synchronized SAIs was chosen for the idle state with $(A/F)_{eng}$ = 13 and t_{ig} = 10°CA BTDC, which corresponds to a typical operating condition without SAI. At cold-start condition, three way catalytic converter was located at l_{cat} = 20 and 30 cm and the base condition was chosen for the idle state with $(A/F)_{eng}$ = 14.5 and t_{ig} = 10°CA BTDC.

3. RESULTS AND DISCUSSION

3.1. Continuous SAI at Cold-Steady Condition

Emission characteristics of HC with continuous SAI are shown in Figure 2 in terms of $(A/F)_{exh}$ for three injection locations. As injection location moves closer to the exhaust valve, HC emissions decrease, which is in accordance with previous work (Kollmann and Zahn, 1994). When the injection location is close to the exhaust valve, the exhaust gas has higher temperature and longer resident time. Consequently, exothermic reaction becomes active. The HC emissions decrease with $(A/F)_{exh}$ when it is rich, while is relatively insensitive when it is lean. With increasing $(A/F)_{exh}$, the oxygen concentration is increased, which could enhance HC reduction. Simultaneously,

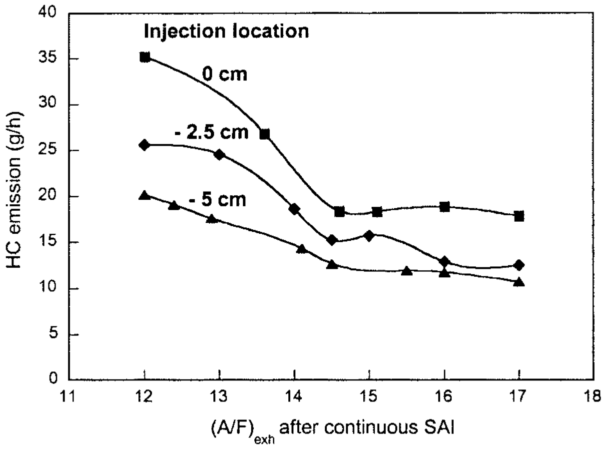

Figure 2. HC emissions with $(A/F)_{exh}$ for continuous SAI at several injection locations for $(A/F)_{eng}$ = 10 and intake pressure 32 kPa (HC emissions without air injection are 42 g/h).

mixture temperature and concentrations of HC, CO and H_2 are decreased, which could inhibit HC reduction. The results suggest that the enhancement is dominant in the rich region and the enhancement and inhibition effects are balanced in the lean region. It also shows that the continuous SAI has much lower HC emissions than the case without having air injection, which produces 42 g/h of HC emissions with the $(A/F)_{eng}$ of 10.

Figure 3 shows exhaust gas temperature along the exhaust pipe for continuous SAI together with the case without having air injection. Exhaust gas temperature decreases gradually along the exhaust pipe in the case without having air injection due to heat loss through exhaust pipe. The temperature difference between the continuous SAI and without having air injection is small from 6 cm to 14 cm, while the difference becomes pronounced along the downstream. This implies that exothermic reaction is marginal down to the location 14 cm downstream of the exhaust port exit and becomes significant farther downstream. The slow exothermic reaction near the exhaust port for continuous SAI can be attributed to the delay in mixing between engine-out exhaust gas and secondary air. As $(A/F)_{exh}$ increases, exhaust gas temperature becomes higher. The exhaust gas temperature with $(A/F)_{exh}$ of 16 is higher than that of 14.5, which implies that the secondary air is not utilized effectively for $(A/F)_{exh}$ = 14.5.

3.2. Synchronized SAI at Cold-Steady Condition

Figure 4 shows the effect of injection timing and pressure for synchronized SAI on the reduction rate of HC emissions for l_{sai} = –5 cm. The location of SAI is chosen to be at 5 cm into the exhaust port. The spark timing is BTDC 10°, $(A/F)_{eng}$ is 10, and $(A/F)_{eng}$ after SAI is stoichiometric. When the SAI pressure varies from 200 to 600 kPa, the SAI duration varies from 468° to 112° CA to supply the same amount of secondary air.

The peak reduction rate of HC occurs at ATDC 230° SAI for all SAI pressures except for 200 kPa. This suggests that the gas mixture at ATDC 230° SAI has temperature high enough to induce exothermic reaction and resides long enough in the exhaust port. As SAI pressure decreases, HC reduction rate is increased for SAI timing between ATDC 50° and ATDC 220° since the injection duration is increased and the amount of secondary air injected after ATDC 230° is increased. For the timing of SAI during the period of exhaust valve closing, the mixture of engine-out exhaust gas and

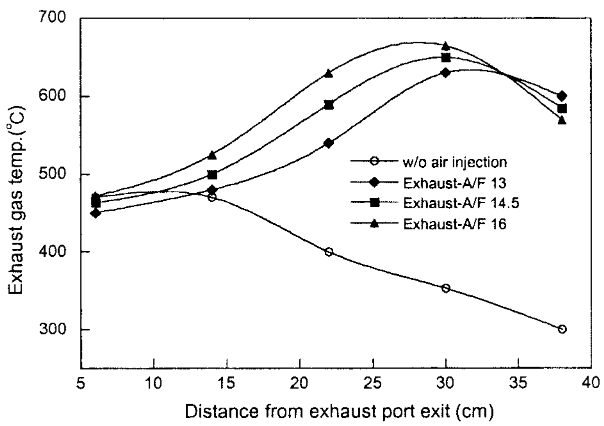

Figure 3. Exhaust gas temperature along exhaust pipe with continuous SAI for $(A/F)_{eng}$ = 10, intake pressure 32 kPa, and l_{sai} = –5 cm.

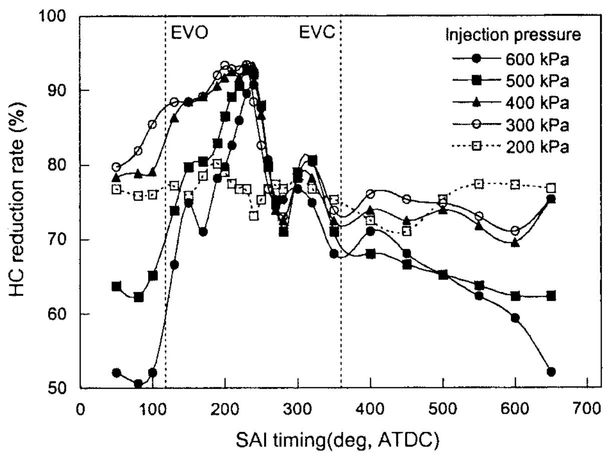

Figure 4. Effect of injection pressure and timing of synchronized SAI on HC reduction rate (l_{sai} = –5 cm, $(A/F)_{eng}$ = 10, and $(A/F)_{exh}$ after SAI is stoichiometric).

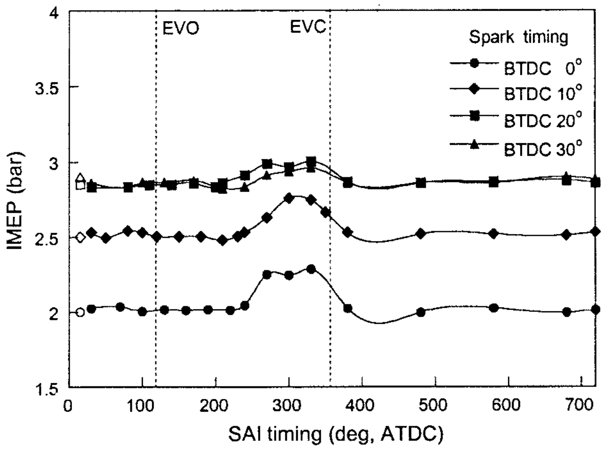

Figure 5. Effect of injection timing of SAI on IMEP for $l_{sai} = 0$, $(A/F)_{eng} = 10$, and $(A/F)_{exh}$ after SAI stoichiometric (Open symbols : IMEPs without having air injection).

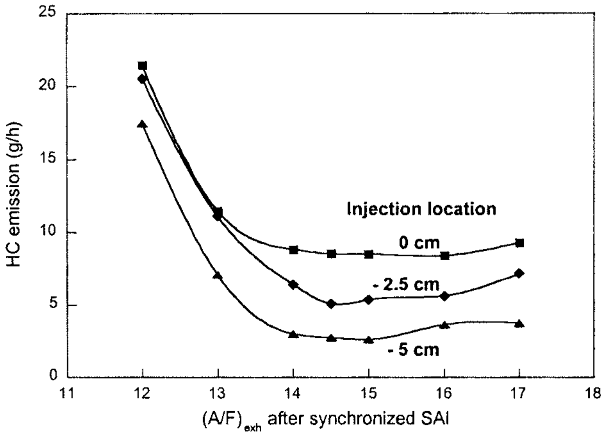

Figure 6. HC emissions with $(A/F)_{exh}$ after synchronized SAI at several injection locations for $(A/F)_{eng} = 10$ and intake pressure 32 kPa (HC emissions without having air injection are 42 g/h).

secondary air has low temperature and does not mix well since the engine-out exhaust gas is relatively stationary. This suggests that significant amount of injected air for continuous SAI, especially during the exhaust valve closed period, cannot be utilized effectively for HC reduction.

The HC reduction rate with 200 kPa is relatively unchanged with SAI timing. It can be attributed to the air injection duration, which is too long to take advantage of SAI timing effect. The application of the high secondary air injection pressure is ascribed to the fact that the air injector used in this test is the one fabricated for use of compressed natural gas (CNG) which has small flow rate. The pressure can be lowered if the gas injector is optimized with bigger flow rate.

Figure 5 shows IMEP variation with injection timing for the synchronized SAI. The results show that compared to the cases without having air injection (open symbols), the cases with synchronized SAI have 5~10% increase in IMEP for the injection timing in the range of ATDC 250~360°. This can be attributed that part of the injected air penetrates into the combustion chamber and is trapped and utilized in the next cycle. Since the combustion chamber is maintained rich, the engine power output is increased with synchronized SAI. However, the HC reduction rate does not increase in this region since secondary air utilized for HC reduction decreases, as indicated in Figure 4.

The HC emissions with $(A/F)_{exh}$ and injection location for synchronized SAI are shown in Figure 6. Engine conditions, $(A/F)_{exh}$, and SAI locations are the same as those as shown in Figure 2. The $(A/F)_{exh}$ is increased by increasing injection duration with SAI pressure of 400 kPa and SAI timing of ATDC 230°. The results show similar trend as those of continuous SAIs in Figure 2. It is noted that synchronized SAI has much lower HC emissions than continuous SAI, implying that the synchronized SAI utilized secondary air for HC reduction more effectively.

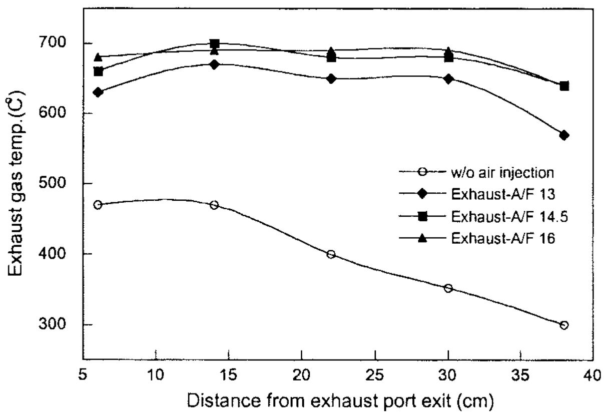

Figure 7. Exhaust gas temperatures along exhaust pipe with synchronized SAI for $(A/F)_{eng} = 10$ and intake pressure 32 kPa.

Figure 7 shows the exhaust gas temperature along the exhaust pipe for the synchronized SAI and the case without having air injection. The location of SAI is 5 cm into the exhaust port, SAI pressure is 400 kPa, and SAI timing is ATDC 230°. The exhaust gas temperatures from 6 cm to 30 cm downstream are almost the same, and the values are high compared to those with the continuous SAI in Figure 3, especially near the exhaust port exit. This result demonstrates that active exothermic reaction occurs along the exhaust pipe between the air injection point and the location of 6 cm downstream of the exhaust port exit. The reason for the fast oxidization is related to the SAI timing of ATDC 230º, where the mixture remained in the exhaust port is almost oxidized while the exhaust valve is closed.

3.3. Cold-Start with Catalytic Converter

Exhaust gas temperature and HC emissions during the cold-start operation are monitored for the first 120 s from the engine start with catalytic converter. The catalytic converter consists of palladium-rhodium formulation at 2.0 g/liter loading and 5:1 ratio and its substrate volume is 0.8 liter which is divided into two bricks with the same volume. Three cases of continuous SAI, synchronized SAI, and the base condition are compared. The base condition is for $(A/F)_{eng} = 14.5$ and optimum SAI timing for synchronized SAI at cold-start is $t_{sai} = 100º$ CA ATDC. The other engine conditions such as spark timing, fuel injection rate, and secondary air injection factors are chosen based on the results from the cold-steady idle operation.

Figure 8 shows the catalytic converter temperature and HC emissions when the catalyst is located at $l_{cat} = 30$ cm. The catalyst temperature for the synchronized SAI is the highest, and the difference between synchronized and continuous SAIs at the initial period (t < 70 s) increases. The elapsed time to attain catalytic converter temperature of 300ºC for the synchronized and continuous SAIs is 72 s and 87 s, respectively. This result shows that both SAIs shorten the catalyst warm-up period. The rate of HC emissions is shown in Figure 8(b). The HC emission rate with the synchronized SAI decreases sharply after the peak HC emissions, even though peak HC emission rates for the base and synchronized SAI are almost the same. This peak HC emission rate is due to the release of absorbed HC when catalyst temperature is cold. The reason for high HC emission rate for the continuous SAI is due to poor HC oxidation at the early stage of cold start. The accumulated HC emission with the continuous SAI is increased by about 7%, while that of the synchronized SAIs is reduced by about 44% at 120 s, compared to that for the base condition.

Figure 9 shows the catalytic converter temperature and HC emissions for $l_{cat} = 20$ cm. The catlytic converter volume is reduced from 0.8 liter to 0.4 liter by removing one brick. The catalyst temperature (a) shows somewhat different trend compared to that of Figure 8. At the initial period (t < 70 s), the catalyst temperature for the synchronized SAI is higher, while that for the continuous SAI is the higher after then. The reason can be attributed to the fact that exothermic reaction at the catalytic converter is active for the continuous SAI, since unreacted HC at the catalytic converter for the continuous SAI is higher than that for the synchronized SAI. The elapsed

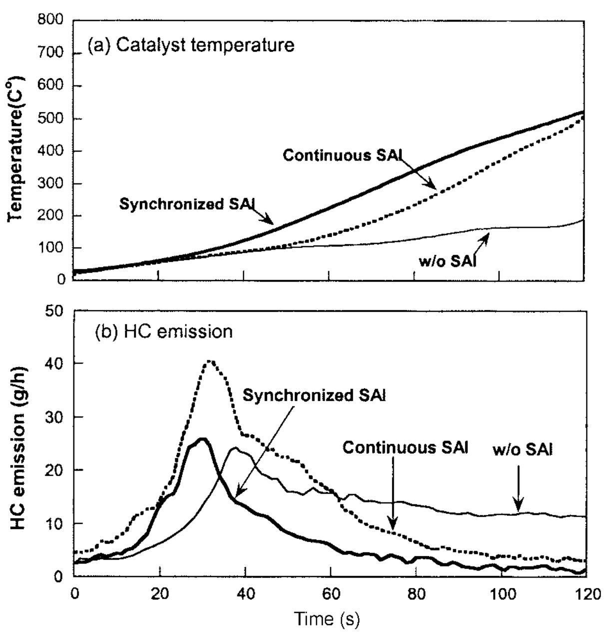

Figure 8. Catalytic converter temperature (a) and HC emissions (b) for $l_{cat} = 30$ cm and $l_{sai} = -5$ cm (both SAIs: $(A/F)_{eng} = 10$ and $(A/F)_{exh} = 14.5$, base condition: $(A/F)_{eng} = 14.5$).

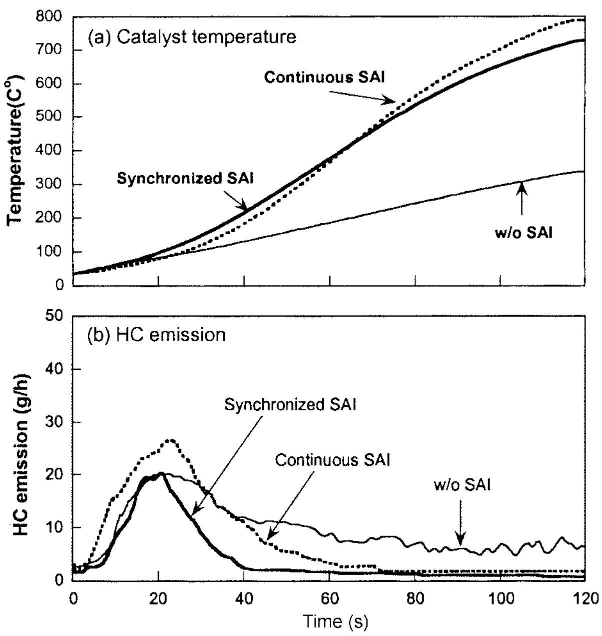

Figure 9. Catalytic converter temperature (a) and HC emission (b) for $l_{cat} = 20$ cm and $l_{sai} = -5$ cm (both SAIs: $(A/F)_{eng} = 10$ and $(A/F)_{exh} = 14.5$, and base condition: $(A/F)_{eng} = 14.5$).

time to attain catalytic converter temperature of 300ºC for the synchronized SAI, the continuous SAI, and the base condition is 51 s, 54 s, and 100 s, respectively. The rate of HC emissions is shown in Figure 9(b). The elapsed time for peak HC emission rate for l_{cat} = 20 cm is shorter than that for l_{cat} = 30 cm. It can be reasoned that the release of the absorbed HCs depends on the catalytic converter temperature. At the initial period ($t < 70$ s), the HC emissions for the continuous SAI are higher than that for the synchronized SAI, while those for both continuous and synchronized SAIs are almost the same after then. It can be attributed to the fact that catalytic converter temperature is high enough to achieve good conversion efficiency for both SAI conditions. The HC emissions with the continuous and the synchronized SAIs are reduced by about 22% and 56% at 120 s, respectively, compared to that for the base condition of $(A/F)_{eng}$ = 14.5.

This result shows that the HC reduction rates for both SAIs increase compared to the base condition, which has the same catalytic converter location, especially when the catalytic converter is located closer to the exhaust port. This implies that exhaust gas temperature is more important for the SAI conditions than for the base condition without having SAI.

5. CONCLUSION

The effect of secondary air injections on the reduction of hydrocarbon emission has been investigated for cold-steady/start conditions.

For cold-steady condition with both continuous and synchronized SAIs, as injection location is closer to the exhaust valve, HC emissions decrease and exhaust gas temperature increases. HC emissions decrease with increasing $(A/F)_{exh}$ when $(A/F)_{exh}$ is rich, and is relatively insensitive when $(A/F)_{exh}$ is lean.

The synchronized SAI is found to be more effective in HC reduction and exhaust gas temperature compared to the continuous SAI.

At cold-start condition, as the catalytic converter is located closer to the exhaust port exit, the HC reduction rates for both SAIs increase compared to the base condition, and the catalytic converter temperature for the continuous SAI increases more rapidly than that for the synchronized SAI.

The accumulated HC emissions for the catalytic converter located at 20 cm during the first 120 s decrease about by 56% and 22% with the synchronized and continuous SAI, respectively, compared to that for the base condition. The elapsed times for catalytic converter to attain light-off temperature with both SAIs decrease by about 50% compared to that with the base condition.

ACKNOWLEDGEMENT−This work was supported by the Hyundai Motor Company through the Institute of Advanced Machinery and Design.

REFERENCES

Cheng, W. K., Summers, T. and Collings, N. (1998). The fast-response flame ionization detector. *Prog. Energy Combust. Sci*. **24**, 89−124.

Crane, M. E., Thring, R. H. and Podner, D. J. (1997). Reduced cold-start rapid exhaust port oxidation (REPO) in a spark-ignition engine. *SAE paper No. 970264*.

Kollmann, K. and Zahn, W. (1994). Secondary air injection with a new developed electrical blower for reduced exhaust emission. *SAE paper No. 940472*.

Kim, I. K., Lee, W. J., Yoon, J. S. and Park, C. K. (2001). An exploratory study of the the emission reduction technologies compliant with SULEV regulations. *International Journal of Automotive Technology* **2**, **2**, 63−75.

Ma, T., Collings, N. and Hands, T. (1992). Exhaust gas ignition (EGI) - A new concept for rapid light-off of automotive exhaust catalysts. *SAE paper No. 920400*.

Sim, H. S., Min, K. and Chung, S. H. (2000). Reducing exhaust HC emission at SI engine using continuous and synchronized secondary air injection. *Seoul 2000 FISITA*, F2000H189.

Sim, H. S., Min, K. and Chung, S. H. (2001). Effect of synchronized secondary air injection on exhaust hydrocarbon emission in a spark ignition engine. *IMechE* **215**, Part D, D06800, 557−566.

Yaegashi, T., Yoshizaki, K., Nagami, T. and Sugiura, S. (1994). New technology for reducing the power consumption of electrically heated catalyst. *SAE Paper No. 940464*.