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An experimental study on the effects of impingement-walls on the spray and combustion characteristics of SIDI CNG †

Yu Liu[1], J. K. Yeom[2] and S. S. Chung[2,*]

[1]Faculty of Aerospace Engineering, Shenyang Aerospace University, Liaoning Shenyang, 110136, China
[2]Department of Mechanical Engineering, Dong-A University, Busan 604-714, Korea

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Abstract

Compressed natural gas (CNG) is regarded as one of the most promising alternative fuels, and maybe the cleanest fuel for the spark-ignition (SI) engine. In the SI engine, direct injection (DI) technology can significantly increase the engine volumetric efficiency and decrease the need of throttle valve. During low load and speed conditions, DI allows engine operation with the stratified charge, and the use of extremely lean fuel-air mixture enables relatively higher combustion efficiency. In this study, a combustion chamber with a visualization system is designed. The spray development and combustion propagation processes SIDI CNG were digital recorded. It was found that high injection pressure reduced the ignition probability significantly because of quenching of flame kernel. To improve the ignition probability, three kinds of impingement-walls were designed to help the mixture preparation. It was found that the CNG-air mixture can be easily formed after spray-wall impingement and the ignition probability was also improved. The results of this study can contribute important data for the design and optimization of spark-ignition direct injection (SIDI) CNG engine.

Keywords: Compressed natural gas (CNG); Spark-ignition (SI); Direct injection (DI); Impingement-wall; Ignition probability

1. Introduction

In order to meet the stringent automobile pollutant legislation and continue to improve the thermal efficiency of internal combustion engines (ICEs), the research work for the development of more efficient and economical ICEs must be conducted [1, 2]. The gasoline direct injection (GDI) engine has also been developed to improve fuel economy. In GDI engines, the DI technology strongly increases the engine volumetric efficiency. DI technology also allows a decrease in the need for throttle valves for control purposes, thus reducing the cycle pumping loss. Furthermore, during low load and speed conditions of DI engines, stratified charge in the combustion chamber permits extremely lean combustion without high cycle-by-cycle variations [3, 4].

Compressed natural gas (CNG) is regarded as one of the most promising alternative fuels [5]. It is composed primarily of methane (CH_4) [6]. CNG has a high octane number and therefore can be easily employed in SI engines. Due to the high octane number, engines can be operated with a higher compression ratio for better thermal efficiency [7]. Furthermore, CNG is also a cleaner fuel than gasoline or diesel in terms of emissions. Since CNG has a low carbon/hydrogen (C/H) ratio, it produces less CO_2 per unit of energy released. Therefore, CNG appears to be an excellent fuel for SI engines [8].

The spark-ignition direct injection (SIDI) CNG engine is a kind of engine which adopts DI technology in a SI engine, and uses the alternative fuel of CNG. Up to now, studies of SIDI CNG engines have concentrated on the CNG homogeneous charge, and few reports can be found related to SIDI CNG engines with the stratified charge [9, 10]. In our previous study, a visualization experiment system consisting of a combustion chamber, fuel supply system, air supply system, electronic control system, and data acquisition system was designed and built. In the experiment, the CNG was injected into the combustion chamber by a GDI injector and then ignited by a spark plug placed near the injector. The ignition probability was examined with various ambient conditions including the injection pressure, air flow velocity, ambient temperature and pressure. It was found that high injection pressure reduced the ignition probability significantly because of quenching of the flame kernel.

In this study, to improve the ignition probability, three kinds of impingement-walls were designed. The spray-wall impingement process, which is caused by the interaction between the spray, the wall and the air, is an important issue

*Corresponding author. Tel.: +82 51 200 7654, Fax.: +82 51 200 7656
E-mail address: sschung@dau.ac.kr
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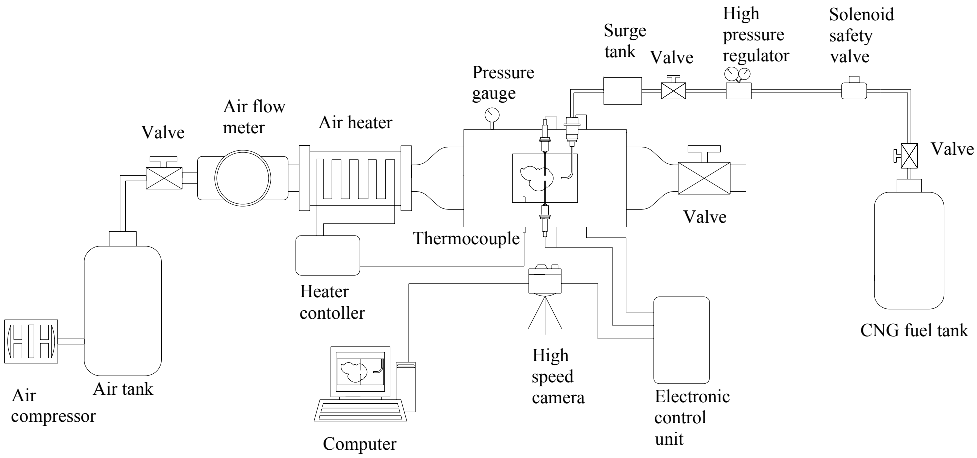
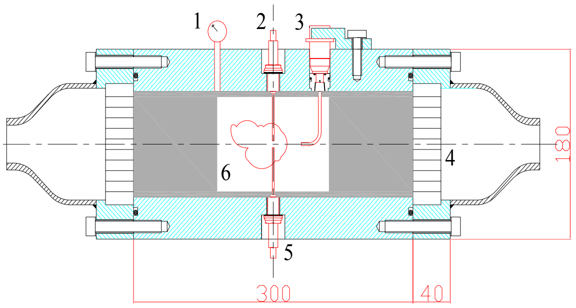


Fig. 1. Schematic apparatus of visualization experiment.



1. Pressure gauge
2. Spark plug center electrode
3. GDI injector
4. Honeycomb-shaped plate
5. Spark plug ground electrode
6. Window

Fig. 2. Sectional view of the combustion chamber.

affecting mixture preparation and consequent combustion [11]. The spray-wall impingement process, ignition probability and the flame propagation process of SIDI CNG were investigated. It was found that the spray-wall impingement process can improve the ignition probability significantly.

2. Experimental apparatus and methods

A visualization experiment was designed and set up to investigate spray and combustion characteristics of SIDI CNG. Fig. 1 shows a schematic apparatus of visualization experiment, which consists of five main parts: a combustion chamber, a fuel supply system, an air supply system, an electronic control system, and an optical system.

2.1 Combustion chamber

A specially devised combustion chamber was designed for this visualization experiment. Fig. 2 shows a sectional view of the combustion chamber. The combustion chamber is 300 mm long, 180 mm wide, and 180 mm high and it has a volume of 2355 cm3. Aluminum was chosen as the material of the combustion chamber. A pressure gauge, a spark plug, a GDI injector, and a thermocouple were installed in the combustion chamber. The spark discharge position is in the center of the combustion chamber. An L-shaped pipe was attached to the GDI injector. The exit of the L-shaped pipe also extended to the center of the combustion chamber. The inside diameter of the L-shaped pipe is 1 mm.

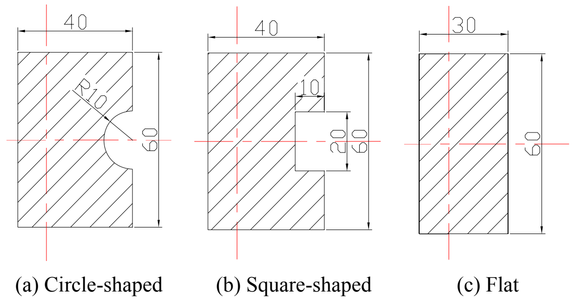


Fig. 3. Structure of impingement-wall.

CNG injection and combustion processes can be examined under different ambient conditions inside the combustion chamber. In this experiment, the maximum possible ambient pressure and temperature were 1 MPa and 400 K, respectively. Air passed through the combustion chamber from one side to the other. To obtain a steady and smooth intake air flow, two honeycomb-shaped plates were located at both sides of the combustion chamber. Two quartz glasses were installed as observing windows to allow the optical system to take CNG spray and combustion images.

2.2 Impingement-wall design

Three kinds of impingement-walls were designed and used to examine the spray-wall impingement process, the ignition probability, and the flame propagation process after the injection start of CNG. Fig. 3 shows three kinds of the impingement-walls include a circle-shaped wall, a square-shaped wall and a flat wall.

Fig. 4 shows the combustion chamber with a circle-shaped impingement-wall. The CNG is injected into the combustion

Table 1. Experimental conditions.

Spark plug position	20 mm from the L-shaped pipe exit
Impingement-wall type	Circle-shaped, square-shaped, flat
Injection pressure (MPa)	1, 3, 5
Ambient pressure (MPa)	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7
Ambient temperature (K)	300
Spark plug gap (mm)	0.5
Spark duration (ms)	0.2
Injection duration (ms)	5
L-shaped pipe inner diameter (mm)	1

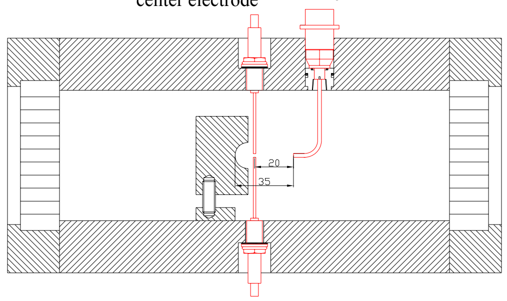


Fig. 4. Combustion chamber with impingement-wall.

chamber by a GDI injector. An L-shaped pipe was attached to the GDI injector and the exit of the L-shaped pipe extended to the center of the combustion chamber. The impingement-wall is placed 35 mm away from the pipe's exit. After the start of injection, CNG passes through the L-shaped pipe first and then penetrates into the combustion chamber. With the CNG's penetration, the injected CNG impinges on the impingement-wall. The spray-wall impingement process helps the mixture preparation and the CNG-air mixture of appropriate composition can be formed near the spark discharge position. In this experiment, the spark plug is placed 20 mm away from the L-shaped pipe's exit and is used to ignite the CNG-air mixture.

2.3 Experimental method

In this experiment, the air flow system mainly contains a compressor, an air tank, two valves and a heater. A K-type thermocouple works with a heater controller to regulate the ambient temperature. Two valves are used to regulate the ambient pressure. The fuel supply system mainly consists of a GDI injector, a CNG tank and a high-pressure regulator. The injection pressure of the injector is adjusted after double decompression by using the pressure regulator. An electronic control unit (ECU) is used to generate control signals including injection timing, injection duration, spark timing and the charge-coupled device (CCD) camera timing. In this experiment, the CNG spray-wall impingement and consequent flame propagation processes were digitally recorded by the CCD camera. Table 1 shows the experimental conditions.

3. Results and discussion

3.1 Spray process with impingement-wall

Fig. 5 shows the CNG spray process without any impingement-wall for 5 MPa injection pressure and 0.5 MPa ambient pressure. With the same experimental condition, Figs. 6, 7 and 8 show the CNG spray-wall impingement process with a circle-shaped, a square-shaped and a flat impingement-wall, respectively.

Shown in Fig. 6, after approximately 3 ms from the injection start, the injected fuel penetrated to the impingement-wall and impinged on it. After impingement, the fuel spray moved along the circle-shaped wall. It was observed that the circle-shaped cavity was filled with two large vortexes on both sides of spray centerline, rotating in the opposite direction. About 1 ms after the spray-wall impingement, the spray began to strip away from the circle-shaped wall at the edge. At the edge of circle-shaped wall re-entrain flow of the CNG spray was generated and the CNG spray flowed in a vortex direction around the spark discharge position. The re-entrain flow of the CNG spray can increase the air entrainment and improve the CNG-air mixing rates. After 7 ms from the injection start, the spray began to move out of circle-shaped cavity and diffused in an upstream direction. The CNG mass fraction in the cavity became gradually smaller and smaller.

Shown in the Fig. 7, the spray-wall impingement process with the square-shaped impingement-wall was observed similar with that of the circle-shaped impingement-wall. There were two large vortexes in the square-shaped cavity and re-entrain flow was generated around the spark discharge position. However unlike the circle-shaped wall, some unusual flow patterns were formed in the corner by the square-shaped wall like small vortex flows. The small vortex flows can make the flow field more turbulent and are regarded to be good for the CNG-air mixing rates.

Fig. 8 shows the CNG spray-wall impingement process with a flat impingement-wall. After impingement, most spray moved along the flat wall and could not diffuse upstream in the axial direction to the spark discharge position. It was shown that the high CNG spray concentration was near the flat wall.

3.2 Combustion process with impingement-wall

It was shown in Figs. 10 and 11 that the flame propagation process with the circle-shaped impingement-wall was similar with that of the square-shaped impingement-wall. A flame kernel was formed with the spark discharge. As the flame kernel grew, it interacted with the turbulent flow field. The turbulent flow field in the cavity made the combustion flame very wrinkled. The combustion flame appeared yellow-white in color surrounded by the light blue flame. With the effect of

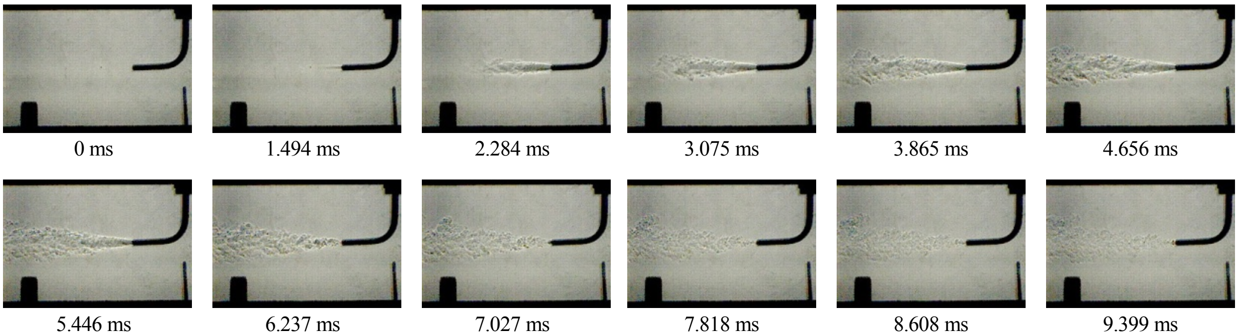


Fig. 5. Spray process without any impingement-wall.

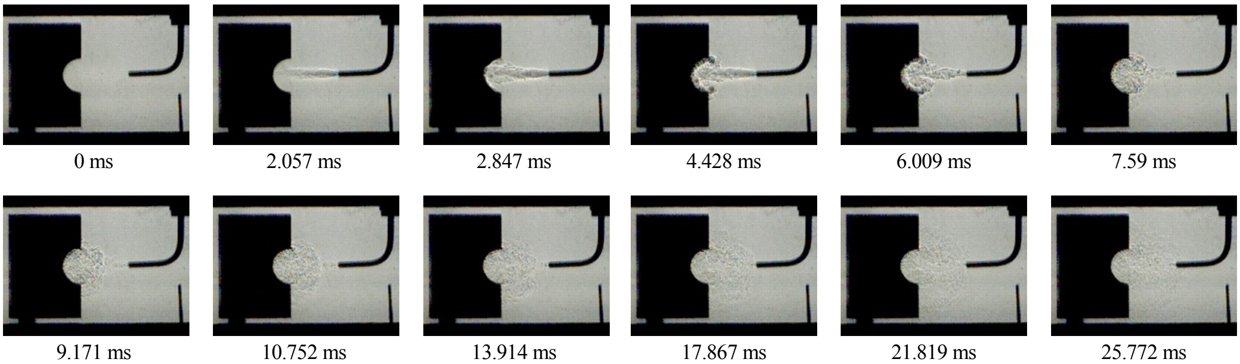


Fig. 6. Spray-wall impingement process with a circle-shaped impingement-wall.

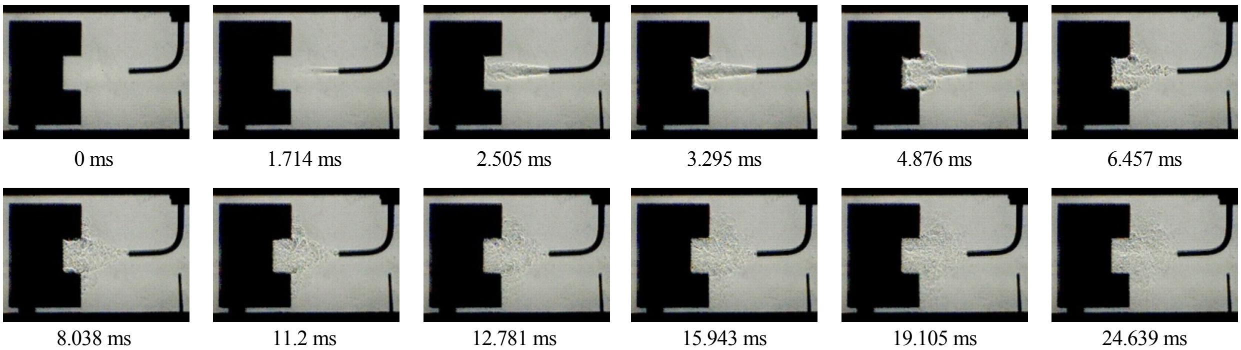


Fig. 7. Spray-wall impingement process with a square-shaped impingement-wall.

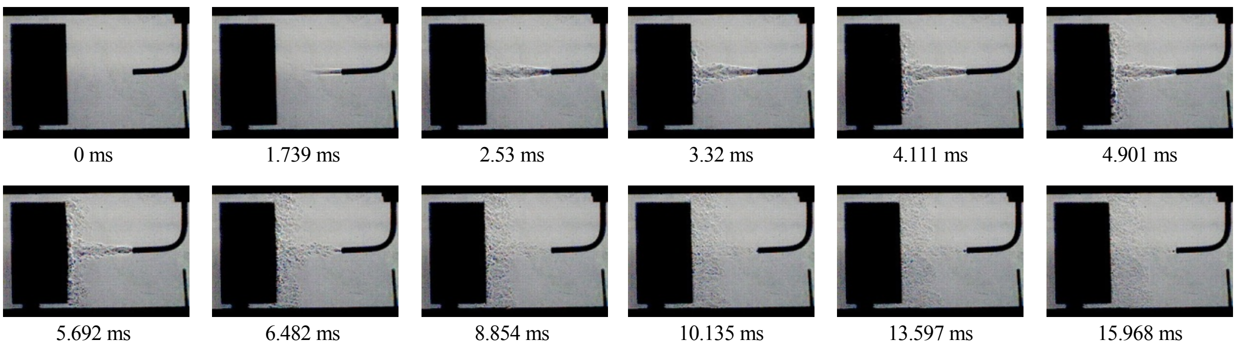


Fig. 8. Spray-wall impingement process with a flat impingement-wall.

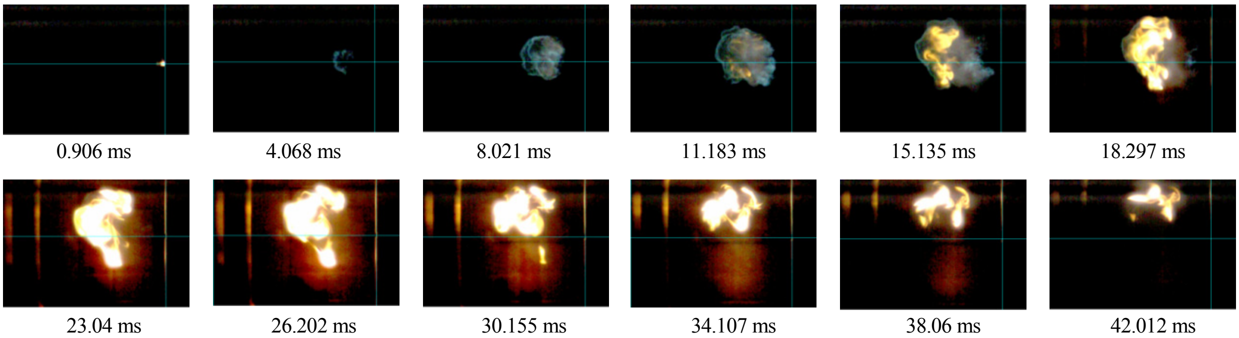


Fig. 9. Flame propagation process without any impingement-wall.

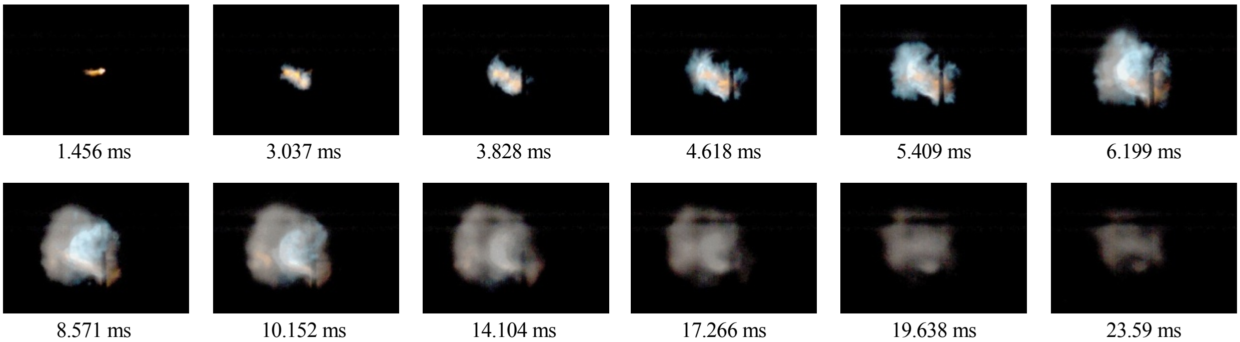


Fig. 10. Flame propagation process with a circle-shaped impingement-wall.

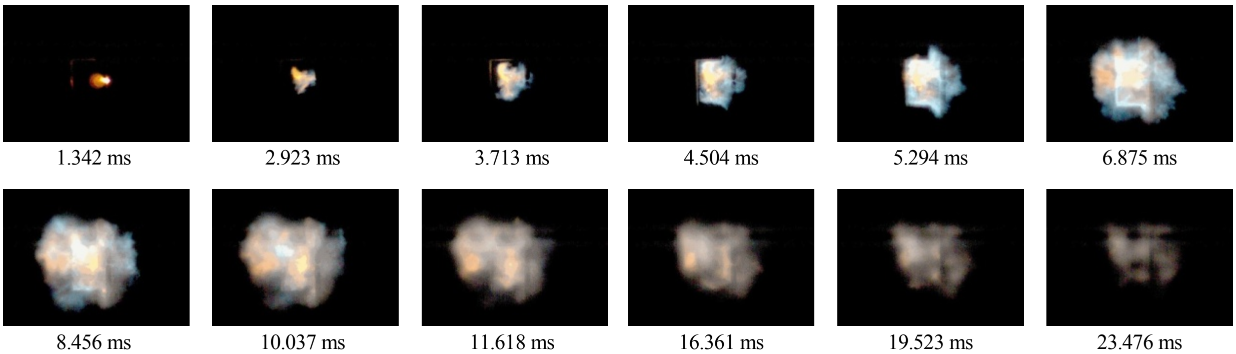


Fig. 11. Flame propagation process with a square-shaped impingement-wall.

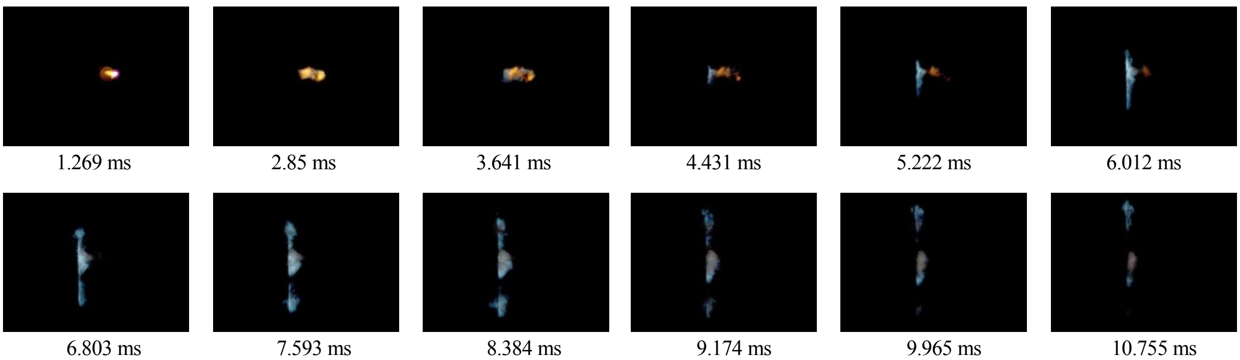


Fig. 12. Flame propagation process with a flat impingement-wall.

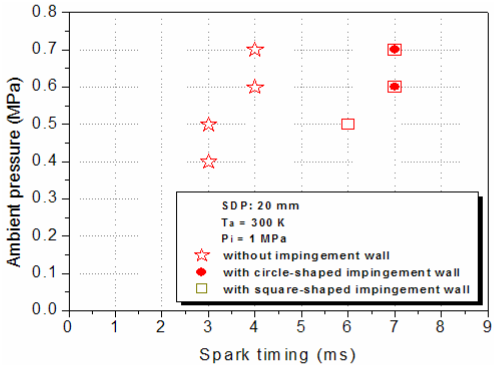


Fig. 13. Ignition probability comparison with 1 MPa injection pressure.

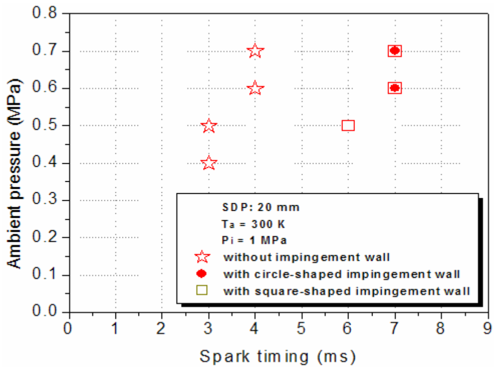


Fig. 14. Ignition probability comparison with 3 MPa injection pressure.

flow field around the spark discharge position, the combustion flame propagated downstream and impinged on impingement-wall. The combustion flame continued to propagate across the combustion chamber and then began to terminate.

Fig. 12 shows the flame propagation process with a flat impingement-wall. It was observed that with the flat impingement-wall, the high spray concentration was near the flat impingement-wall. The spray concentration around the spark discharge position was relatively lower, so it is hard to achieve the ignition with a flat impingement-wall. It was observed that the combustion duration with a flat impingement-wall was quite short compared with that of other kinds of impingement-walls. The result indicates that only a little part of the injected CNG was burned.

3.3 Ignition probability with impingement-wall

Successful ignition, in this work, is defined as flame kernel formation, as a result of a spark discharge, followed by a flame propagation that results in a stable flame. It can be defined that if the ignition probability is above 80%, it is regarded that the mixture can be ignited under this condition and then it is marked on a graph (see Figs. 13, 14 and 15 and in these figures SDP is the short form of spark discharge position).

Fig. 13 shows the ignition probabilities of the CNG sprays

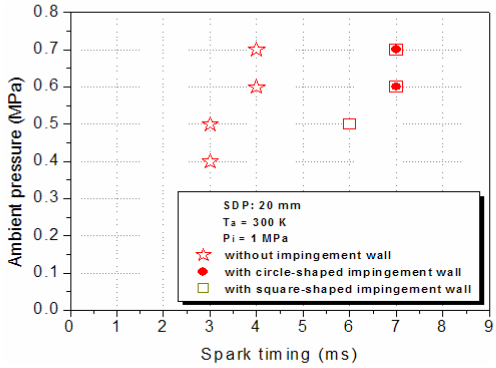


Fig. 15. Ignition probability comparison with 5 MPa injection pressure.

without an impingement-wall and with three kinds of impingement-walls under 1 MPa injection pressure. The spark discharge position was 20 mm from the exit of L-shaped pipe. Ambient temperature was set to 300 K and the ambient pressure was set from 0.1 to 0.7 MPa. The figure shows that the CNG-air mixture can be easily ignited between 0.4 and 0.7 MPa ambient pressures with proper spark timings. As we know, the instantaneous spray velocity value and the spray concentration at the spark discharge position play the important roles in determining the success of the ignition. And high ambient pressure controls the spray velocity of the injected fuel and improves the spray concentration. So under relatively higher ambient pressure, the mixture can be ignited more easily.

In this study, the spark timing is the time that a spark will occur relative to the start of injection. The spark timing is an important parameter for a successful ignition. For the ignition without any impingement-wall the proper spark timing was between 3 and 4 ms. For the ignition with the an impingement-wall the proper spark timing was between 6 and 7 ms. The difference in proper spark timings is due to the different mechanisms that form the mixture. For the ignition with an impingement wall, the mixture with appropriate composition is formed by the spray-wall impingement process, so it takes more time to prepare the CNG-air mixture compared with the ignition without any impingement wall.

Fig. 14 shows the ignition probabilities under 3 MPa injection pressure. It was found that without an impingement-wall to obtain successful ignition the injection pressure can only be set at 1 MPa. With impingement-walls the injection pressure can be set at 3 and 5 MPa. High injection pressure leads to high spray velocity, so for the ignition without any impingement-wall, it is hard to achieve the ignition because of the quenching of flame kernel by the high spray velocity. However with an impingement wall, because the spray-wall impingement process causes a loss of kinetic energy, the spray velocity is reduced and the quenching of flame kernel is no longer as significant.

It was observed that the ignition probability with a circle-shaped impingement-wall was almost the same as that with square-shaped impingement-wall. However, the ignition probability with a square-shaped impingement-wall was a little better. It has been discussed before that some unusual flow patterns were formed in the corner by the square-shaped wall like small vortex flows and the small vortex flows can make the flow field more turbulent. This is the reason why the ignition probability with the square-shaped impingement-wall is better.

Fig. 15 shows the ignition probabilities of the CNG sprays without an impingement-wall and with three kinds of impingement-wall under 5 MPa injection pressure. It was observed that for both ignitions with the circle-shaped impingement-wall and square-shaped impingement-wall, with the increase of injection pressure, the ignition probability increased. For the ignition with a flat impingement wall, the CNG-air mixture could be ignited under 0.5 to 0.7 MPa ambient pressures only for 5 MPa injection pressure. And the proper spark timing was 6 and 7 ms.

4. Conclusions

In this study, three kinds of impingement-walls were designed and their effects on the SIDI CNG's spray-wall impingement process, flame propagation process and ignition probability were investigated. The SIDI CNG's spray-wall impingement and flame propagation processes were digitally recorded using a CCD camera. The ignition probabilities with impingement-walls were examined and also compared with those without an impingement-wall. The findings can be summarized as follows:

(1) With a circle-shaped impingement-wall, it was observed that the circle-shaped cavity was filled with two large vortexes, rotating in the opposite direction and re-entrain CNG spray flow was generated. With a square-shaped impingement-wall, some small vortex flows which are regarded as good for the CNG-air mixing rates were observed in the corner by the square-shaped wall. With a flat impingement-wall, after impingement most of the CNG spray moved along the flat wall and high spray concentration was near the flat wall.

(2) The similar flame propagation processes were observed with a circle-shaped and a square-shaped impingement-wall. A flame kernel was formed with the spark discharge. The turbulent flow field in the cavity made the combustion flame very wrinkled. After ignition, the combustion flame propagated downstream and impinged on the impingement-wall. For the flame propagation process with a flat impingement-wall, because the high spray concentration was near the impingement-wall, it was hard to achieve ignition.

(3) High ambient pressure controls the injected spray velocity and improves the spray concentration, so under relatively higher ambient pressure, the mixture can be ignited more easily. The proper spark timing was delayed for the spray-wall impingement combustion compared to that without an impingement-wall because of the different mechanisms that form the mixture.

Acknowledgment

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References

[1] Z. H. Hang, K. Zheng and Z. L. Yang, Visualization study of natural gas direct injection combustion, *Transactions of CSICE*, 20 (6) (2002) 511-520.

[2] Z. H. Hang, K. Zheng and Z. L. Yang, Study on combustion characteristics of direct injection natural gas engine by using a rapid compression machine, *Transactions of CSICE*, 19 (4) (2001) 314-322.

[3] K. Zeng, Z. H. Huang, B. Liu, L. X. Liu, D. M. Jiang, Y. Ren and J. H. Wang, Combustion characteristics of a direct-injection natural gas engine under various fuel injection timings, *Applied Thermal Engineering*, 26 (8-9) (2006) 806-813.

[4] S. Kono, Study of the stratified charge and stable combustion in DI gasoline engines, *JSAE Review*, 16 (4) (1995) 363-368.

[5] A. M. Pourkhesalian, A. H. Shamekhi and F. Salimi, Alternative fuel and gasoline in an SI engine: A comparative study of performance and emissions characteristics, *Fuel*, 89 (5) (2010) 1056-1063.

[6] D. Fino, N. Russo, G. Saracco and V. Specchia, CNG engines exhaust gas treatment via Pd-Spinel-type-oxide catalysts, *Catalysis Today*, 117 (4) (2006) 559-563.

[7] D. Fino, N. Russo, G. Saracco and V. Specchia, Supported Pd-perovskite catalyst for CNG engines' exhaust gas treatment, *Progress in Solid State Chemistry*, 35 (2-4) (2007) 501-511.

[8] P. H. Barros Zárante and J. R. Sodré, Evaluating carbon emissions reduction by use of natural gas as engine fuel, *Journal of Natural Gas Science and Engineering*, 1 (6) (2009) 216-220.

[9] H. Kamura and K. Takada, Development of in-cylinder gasoline direct injection engine, *JSAE Review*, 19 (2) (1998) 175-180.

[10] M. Gäfvert, K. E. Årzén, L. M. Pedersen and Bo Bernhardsson, Control of GDI engines using torque feedback exemplified by simulations, *Control Engineering Practice*, 12 (2) (2004) 165-180.

[11] L. Andreassi, S. Ubertini and L. Allocca, Experimental and numerical analysis of high pressure diesel spray-wall interaction, *International Journal of Multiphase Flow*, 33 (7) (2007) 742-765.

Yu Liu received his Ph.D in Mechanical Engineering from Dong-A University, Busan, Korea in 2011. He is currently a lecturer at Shenyang Aerospace University in China. He is interested in engine combustion mechanism, combustion simulation and engine substitute fuel.

Jeong Kuk Yeom received his Ph.D in Mechanical Engineering from Doshisha University, Kyoto, Japan in 2001. In 2006, he joined the Department of Mechanical Engineering, Dong-A University, Busan, Korea, where he is currently a professor in the Department of Mechanical Engineering. He is interested in diesel spray and biodiesel fuels.

Sung Sik Chung received his Ph.D in Mechanical Engineering from Keio University, Tokyo, Japan in 1995. In 1984, he joined the Department of Mechanical Engineering, Dong-A University, Busan, Korea, where he is currently a professor in the Department of Mechanical Engineering. He is interested in engine combustion analysis and alternative fuel.