

A STUDY ON THE EFFECT OF WALL TEMPERATURE ON KNOCK PHENOMENA USING A SINGLE CYLINDER SPARK-IGNITED ENGINE

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ABSTRACT –

Due to its intrinsic characteristics of spark-ignited engine, engine operation under high compression ratio can bring to high efficiency but also can invoke the knock which can cause mechanical failure. Because knock is highly dependent on in-cylinder thermal boundary condition, it is important to investigate the relationship between in-cylinder condition and wall temperature. Therefore, this study mainly focuses on the effect of cylinder wall temperatures on knock phenomena.

Dual-loop coolant passages for cylinder head and liner facilitated the control of independent coolant temperature. It was enabled to investigate the effect of each component. By temperature measurements around the combustion chamber, as a coolant temperature variation does not affect a lot to the other's wall temperature, it was verified that independent wall temperature control was achieved. Also, piston surface temperature was found to be governed by liner wall temperature.

In addition, by refined experimental methodologies, the knock mitigation effect was observed by the load limit expansion. It was found that head cooling strategy has a significant role on knock mitigation. For deeper understanding, 3D CFD simulation was used in this study. As the result, it was found that the intake port wall is highly influential on the heat transfer to gas during the gas induction phase. In addition, excluding the heat transfer in the intake port, it was found that the liner cooling strategy has a remarkable potential to reduce the gas temperature for knock suppression.

INTRODUCTION

Recently, as the concern about global warming is increasing, regulations on exhaust gas emissions are being reinforced around the world. Among the various regulations, CO₂ regulation is essentially calling for improvement on fuel efficiency due for less fuel consumption of vehicles. A large number of strategies to reduce fuel consumption including high compression ratio, are applied during the engine development process. Increasing the compression ratio of an engine design has been well known to be one of the most effective ways to improve fuel efficiency. However, increasing compression ratio in SI engine is restricted by increased unburned gas temperature which generates knock-prone in-cylinder condition.

Knock is a phenomenon in which the unburned mixture auto-ignites and detonates due to the increased temperature and pressure by combustion process. Not only does this violent combustion bring engine noise, but also it invokes abnormally stiff heat release rate which may lead to damage of mechanical parts including combustion chamber [1, 2, 3]. Therefore, understanding of the knock phenomenon and suggesting proper strategies for its suppression are important.

Practically, using proper engine cooling strategy can be effective to mitigate knock by reducing air-fuel temperature. Hwang et. al. [8] applied a split cooling system. The coolant passages in the cylinder block and the head were controlled. It resulted to 1-3 CA advance of knock limit spark advance (KLSA) with an effective knock suppression. Imaoka, et. al. [9] conducted an analysis on heat transfer from each surface of engine component by using 3D CFD simulation. It was shown that the largest amount of heat was transferred from the intake port to the gas mixture. Asif et. al. [10] investigated the effect of temperature and flow rate of coolant in terms of KLSA. They concluded that coolant condition has no significant effect on knock mitigation, which only resulted in 0.5-1 CA advance of KLSA timing for 10K of coolant temperature decrement.

Takahashi et al. [11] in their 3D CFD simulation work, showed the effect of a liner temperature distribution on in-cylinder condition. They elucidated that in-cylinder air mixture temperature is more affected by exhaust side rather than intake side of liner wall, due to intake air flow motion at the beginning of intake process. Therefore, to reduce ring friction loss of a piston, they proposed a strategic cooling: decreasing the exhaust side temperature while increasing the intake side.

In this study, effect of coolant temperature on knocking phenomena was observed using not only experimental approach but 3D CFD simulation. Firstly, using independent coolant temperature control, relationship between coolant temperature and wall temperature was investigated. Secondly, the effect of coolant temperature was investigated in concern of knock limit load expansion by test under various coolant temperature conditions. Lastly, 3D CFD simulation was applied for deeper understanding of heat transfer between mixture gas and cylinder walls.

KNOCK METRIC

Proper determination of knocking level or status is important because it represents the possibility of damage on engine components by knock. However, it inevitably varies due to natural stochastic behavior mainly due to in-cylinder cyclic variation [7]. In previous studies, several methods have been developed and compared each other to define the knocking status more precisely with less dependency on stochasticity [5, 12, 13].

In this paper, MAPO-TVE (Maximum amplitude of pressure oscillation - threshold value exceed) method with threshold value of 0.5 bar, was applied to determine the knocking cycle. Cylinder pressure signal was filtered with 5th order Butterworth bandpass filter on frequency range of 4-28 kHz. To monitor the knocking level, at least 1000 of consecutive cycles were used for proper statistics. Experiments were conducted under the condition of 15% of knock incidence (150 knocking cycles / 1,000 total cycles) and the tolerance was 1%. Figure 1 shows the correlation between the ISPO knock intensity and MAPO knock incidence. A substantial correlation (R-square = 0.98) was achieved. ISPO is the most widely used index for knock intensity, however, it requires signal processing while MAPO can be obtained with simple designed circuit.

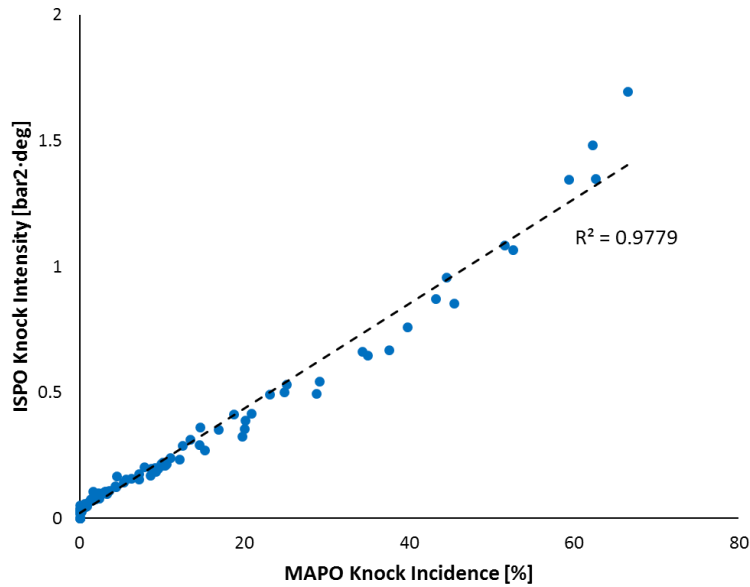


Figure 1 Correlation between MAPO and ISPO

EXPERIMENTAL SETUP

Test Engine

The engine used for experiment is a spark-ignited MPI single cylinder engine (shown in figure 2) of which the bore and stroke are 81mm and 97mm, respectively. This engine was designed to have dual-loop coolant passages in the cylinder head and the liner to control temperatures of wall boundaries independently. Detailed specifications are shown in Table 1.

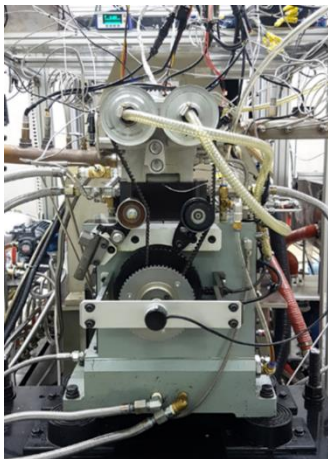


Figure 2 Test engine

Engine Type	Spark-ignited Single Cylinder MPI Engine
Displacement Volume	497 cc
Bore x Stroke	81 mm x 97 mm
Connecting Rod	150.9 mm
Compression Ratio	12

Table 1 Engine specification

Test Cell Setup

The Figure 3 shows the schematic diagrams of experimental setup. Kistler 6065A, a piezoelectric in-cylinder pressure sensor, was installed on the engine and the pressure sensor

signal was amplified with AVL Micro IFEM. Combustion data were monitored and logged with AVL Indimodule combustion analyzer. In-cylinder pressure signal was simultaneously monitored with NI-CRIO platform to observe real-time knock status and knock intensity.

Injection duration and ignition timing were controlled by NI-CRIO platform which enabled to control injection time with micro-second and ignition timing in 0.1 CA. The OVAL CA001 flow meter was used to monitor the fuel injection mass flow rate. Air-fuel ratio during engine test was monitored with HORIBA MEXA-110λ to maintain stoichiometric condition. The composition of exhaust gas was measured using an exhaust gas analyzer, Horiba MEXA-7100 DEGR. To measure the temperature of wall boundaries, thermocouples were installed on 1mm outside from the surfaces the combustion chamber and the liner wall. The Figure 4 shows the location of installed thermocouples on each wall.

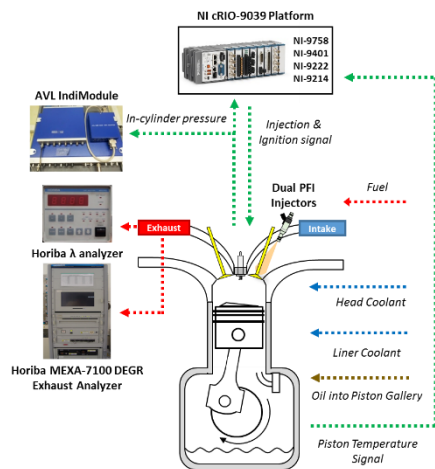


Figure 3 Test cell configuration

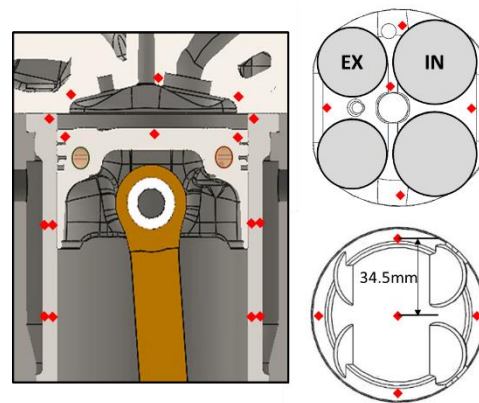


Figure 4 Temperature measurement position

Experiment Condition

Before conducting the experiment, the engine test was carried out to investigate the relation between wall and coolant temperatures. The wall temperatures were measured under various coolant temperature conditions. The operating parameters were fixed to exclude the effect of engine load on the wall temperature.

To evaluate the effect of coolant temperature on knock, engine experiment was conducted changing coolant temperatures of from 40°C to 80°C. The engine operation parameters were determined based on knock incidence. The knock incidence was maintained to be 15% in the number of cycles by changing the amount of fuel injected, while the spark timing was fixed. With 80°C of both coolant temperature, the knock limit load was IMEP of 5.95 bar with 15% of knock incidence. After determining that base condition, the temperature of the head coolant was decreased while the liner coolant was maintained at 80°C. Secondly, the head coolant was heated up to be 80°C and the liner coolant was cooled down. Lastly, to examine the maximum effect of cooling strategy, both coolant temperatures were decreased simultaneously.

Experiment Result

Dependency of Wall and Coolant Temperatures

Figure 5 shows the effect of head coolant on the wall temperatures. The liner coolant was fixed at 85°C and the head coolant was varied from 85°C to 60°C. The red line with circular dot indicates the head wall temperature and the blue line with square dot is showing the liner wall temperature. It appears that the head coolant has little effect on the liner wall while the head wall changed following the change of the head coolant. Figure 6 shows that the liner coolant has large effect on the liner wall.

Figure 7 describes dependency of the piston wall temperature on each coolant temperature. The red line with circular dot shows the piston wall temperature when head coolant temperature varied from 60°C to 85°C (the liner coolant was maintained at 85°C.) The blue line with square dot indicates the case when the liner coolant is cooled down (the head coolant was fixed at 85°C.) Lastly, the black line with triangle dot depicts when the both coolants were cooled simultaneously. It is shown that the piston wall is largely affected by the liner coolant, and the head coolant does not have much effect on the piston wall temperature.

From these results, it can be concluded that the boundary wall temperatures were affected only by certain coolant temperature. It enabled to separate the effect of both coolants on in-cylinder mixture state.

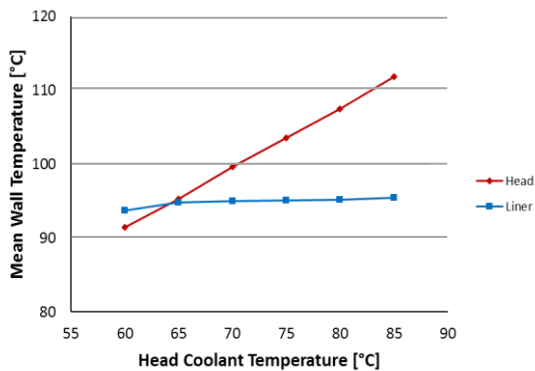


Figure 5 Walls and head coolant temperatures

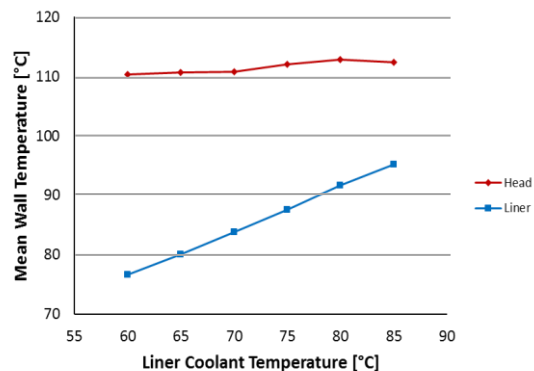


Figure 6 Wall and liner coolant temperatures

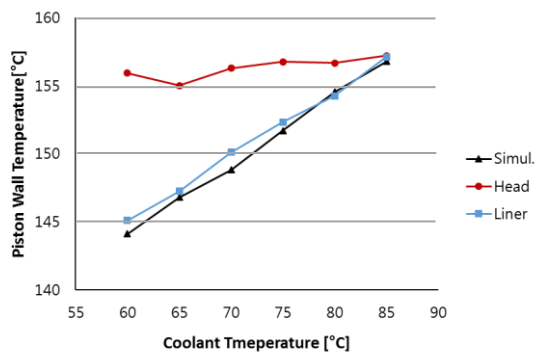


Figure 7 Piston wall and coolants temperatures.

Knock Limit Load Expansion

The effect of each coolant temperature on knock is quantified by knock limit load expansion. As explained in previous section, the knock incidence was maintained to be 15 % of cycles. For base case, the coolants were maintained at 80°C and the ignition timing was fixed at bTDC21 CA.

The figure 8 displays the knock limit load under each coolant condition. Head coolant temperature was changed from 80°C to 40°C and the liner coolant temperature is fixed at 80°C. The head cooling resulted in 1.24 bar of IMEP increase, eventually, which is 20.7% improvement compared to the base condition. Figure 9 shows the result of the liner coolant cooling case. The liner coolant was varied in the same way with the former implementation. As a result, 0.73 bar of IMEP increase (12.3% of improvement) was achieved by cooling the liner coolant to 40°C. Therefore, it is apparent that the temperature of head coolant has greater effect on knock than that of liner coolant temperature.

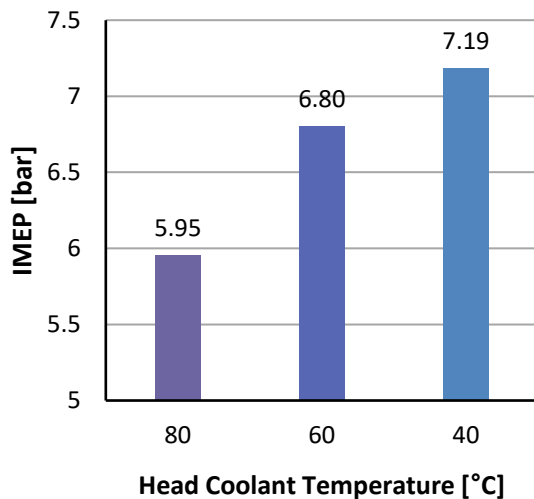


Figure 8 Knock limit expansion under head cooling

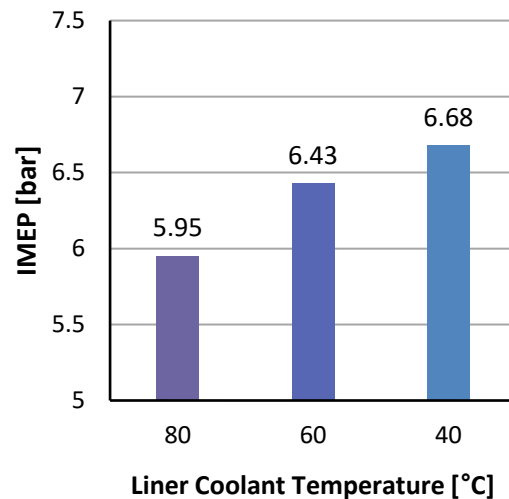


Figure 9 Knock limit expansion under liner cooling

3D CFD ANALYSIS

Simulation Condition

In order to investigate the effect of each wall temperature on heat transfer in detail, 3D CFD analysis was conducted. The simulation was carried out with STAR-CD v4.24 software. The k- ϵ RNG turbulence model was used. PISO (Pressure-Implicit with Splitting of Operators) algorithm was applied for pressure and velocity. To investigate the interactions between wall and gas mixture, the Angelberger wall function was applied. The engine geometry and applied model are given in Figure 10 and Table 2.

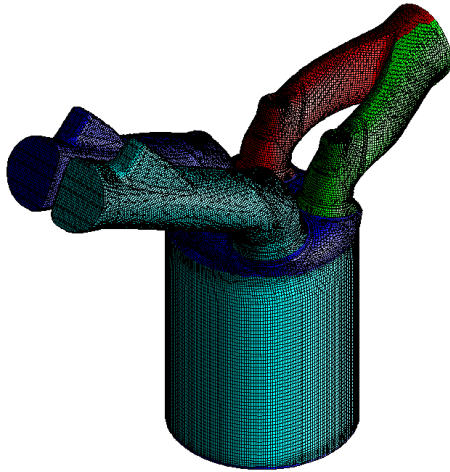


Figure 10 Mesh for simulation at BDC

Program	STAR-CD V4.24
The Number of Mesh	~ 1120000 @ BDC
Turbulence Model	k-ε RNG Model
Heat Transfer Model	Angelberger wall function
Boundary Condition	Intake Pressure: WOT Temperature: Fixed / Adiabatic

Table 2 Simulation configuration

Boundary Condition

The table 3 describes the boundary condition of each case in this study. The simulation was implemented varying temperatures of wall boundaries. The measured wall temperature from the engine test was used as the base case for the simulation. For other cases, wall boundary temperatures were lowered by 20K to investigate the contribution of wall temperature change on heat transfer during the intake process.

Case #	Boundary Wall Temperature [°C]				
	Piston	Liner	Head	Valve Face	Intake Port
1	165	110	115	←	85
2	165	110	95	←	60
3	165	90	115	←	85
4	145	110	115	←	85

Table 3 Calculation boundary condition

Calculation Result

Figure 11 shows the total amount of heat transfer by each wall boundary during intake process under each boundary conditions. It appeared that the intake port shows the largest amount of heat transfer, accounting approximately 35% of total heat transfer in the case 1. Over 24% was found to exist in the intake port under all conditions. It appears that both the piston and the liner also transfers large amount of heat, 22% each in the case 1.

In the case 2, the wall temperatures related to the cylinder head were lowered by 20K. It resulted in 21.1% reduction of heat transfer compared to case 1. It is mostly attributed to the reduction of heat transfer from the intake port wall which accounted for 16.1% of reduction. The case 3 and case 4, which lowered temperatures of the liner and piston by 20K, showed a

little amount of heat decrease compared to case 2. Heat transfer decrease of 7.3% and 3.5% were observed. However, in case 2, considering the head surface itself contributes only 5%p on the heat reduction, cooling liner wall cannot be neglected in reduction of heat transfer.

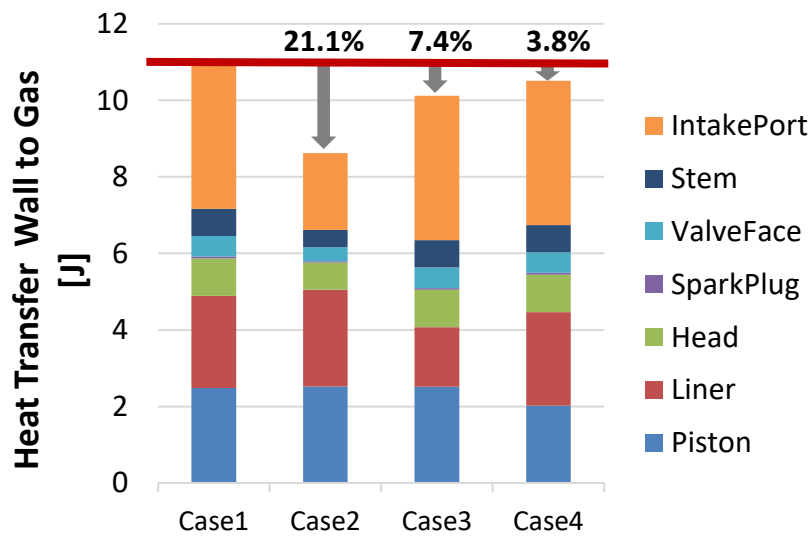


Figure 11 Total amount of heat transfer from wall to gas

SUMMARY & CONCLUSION

In this study, the effect of coolant temperature and wall boundary temperature on knock was investigated by experiment and simulation using 3-D CFD analysis. In experimental way, the dual-loop coolant passage was applied to a single cylinder SI engine to investigate the effect of coolant temperature on the actual wall boundary temperature and knock occurrence. In order to analyze the experimental result in detail, the CFD simulation was used for the analysis of heat transfer during intake stroke.

The tests on the relation between boundary wall and coolant temperatures showed that the wall temperature is affected by the coolant through certain passage. In the case of the piston, it was found that the liner coolant has larger effect on the piston wall temperature than the head coolant has. The load expansion experiment showed that the head coolant temperature shows large effect on knock mitigation than the liner coolant does. Therefore it was possible to achieve higher knock limit load, expanded approximately 20.7%. Additionally, cooling the liner coolant appeared to be effective strategy on knock mitigation showing 12.3% of knock limit load expansion.

The CFD analysis was introduced for detailed understand of the effect of each wall temperature on heat transfer to gas mixture from wall. The simulation was carried out under various wall temperature conditions during intake process. As a result, it was found that the most of heat transfer is invoked through the intake port wall, over 25% of total amount of heat for all the cases. When the temperatures of walls related to the cylinder head was decreased by 20K, 21.1% of heat reduction was achieved. Furthermore, of 21.1% decrease, 16.1%p was attributed to the intake port wall. This result indicated that cooling the head coolant can be effective strategy on reducing heat transfer to gas mixture, supporting the tendency of the experiment result.

REFERENCES

- [1] Nates, R. and Yates, A., "Knock Damage Mechanisms in Spark-Ignition Engines," SAE Technical Paper 942064, 1994, doi:10.4271/942064.
- [2] Fitton, J. and Nates, R., "Knock Erosion in Spark-ignition Engines," SAE Technical Paper 962102, 1996, doi:10.4271/962102.
- [3] Cavina, N, et al., "Investigation of Knock Damage Mechanisms on a GDI TC Engine," SAE Technical Paper 2017-24-0060, 2017, doi:10.4271/2017-24-0060.
- [4] Draper, C., "The Physical Effects of Detonation in a Closed Cylindrical Chamber," NASA Report No. 493, 1934.
- [5] Millo, F. and Ferraro, C., "Knock in S.I. Engines: A Comparison between Different Techniques for Detection and Control," SAE Technical Paper 982477, doi:10.4271/982477.
- [6] Worret, R., Bernhardt, S., Schwarz, F., and Spicher, U., "Application of Different Cylinder Pressure Based Knock Detection Methods in Spark Ignition Engines," SAE Technical Paper 2002-01-1668, 2002, doi: 10.4271/2002-01-1668.
- [7] Bertola, A., Stadler, J., Walter, T., Wolfer, P. et al., "Pressure Indication during Knocking Conditions," KISTLER Special Print No. 920-349e-11.06.
- [8] Hwang, K., Hwang, I., Lee, H., Park, H. et al., "Development of New High-Efficiency Kappa 1.6L GDI Engine," SAE Technical Paper 2016-01-0667, 2016, doi:10.4271/2016-01-0667.
- [9] Imaoka, Y., Shouji, K., Inoue, T., and Noda, T., "A Study of Combustion Technology for a High Compression Ratio Engine: The Influence of Combustion Chamber Wall Temperature on Knocking," SAE Int. J. Engines 9(2):2016, doi:10.4271/2016-01-0703.
- [10] Asif, M., Giles, K., Lewis, A., Akehurst, S., et al., "Influence of Coolant Temperature and Flow Rate, and Air Flow on Knock Performance of a Downsized, Highly Boosted, Direct-Injection Spark Ignition Engine," SAE Technical Paper 2017-01-0664, 2017, doi:10.4271/2017-01-0664.
- [11] Takahashi, D., Nakata, K., and Yoshihara, Y., "Engine Thermal Control for Improving the Engine Thermal Efficiency and Anti-Knocking Quality," SAE Technical Paper 2012-01-0377, 2012, doi:10.4271/2012-01-0377
- [12] Shahlari, A. and Ghandhi, J., "A Comparison of Engine Knock Metrics," SAE Technical Paper 2012-32-0007, 2012, doi:10.4271/2012-32-0007.
- [13] Shahlari, A. and Ghandhi, J., "Pressure-Based Knock Measurement Issues," SAE Technical Paper 2017-01-0668, 2017, doi:10.4271/2017-01-0668.