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Research Paper

Effects of the exhaust gas heat recovery system with a plate heat exchanger on the warm-up performance characteristics of the gasoline engine

Chan-JungKim [1] *, Sank-Wook-Han [2], Ki-Hyun Kim [3], Moo-Yeon Lee [4], Gee-Soo Lee [5]

[1] *Department of Mechanical Design Engineering, Pukyung National University, Republic of Korea*
[2] *Clean Engine R&D Center, Korea Automotive Technology Institute, Republic of Korea*
[3] *Division of Mechanical Convergence Engineering, Silla University, Republic of Korea*
[4] *Department of Mechanical Engineering, Dong-A University, Republic of Korea*
[5] *Department of Smart Automotive Engineering, Youngsan University, Republic of Korea*
**Corresponding author E-mail: cjkim@pknu.ac.kr*

Abstract

Background/Objectives: To meet the regulations for the fuel economy, an EHRS (Exhaust gas Heat Recovery System, which was installed within the vehicle exhaust system and recovered the heat from the exhaust gas, were needed. The EHRS enabled the engine to achieve the fast warm-up performance for reducing friction loss during the cold start.The objective of this paper was to investigate the effects of the design parameters of the EHRS with a plate heat exchanger on the warm-up performance of a gasoline engine.
Methods/Statistical analysis: The EHRS with the plate heat exchanger was manufactured and installed behind the catalyst in the exhaust system of the gasoline direct injection engine. The experimental study and multi-disciplinary analysis were carried out to investigate the effects of the EHRS on the warm-up performance of the engine, such as the coolant temperature, the exhaust gas temperature and the recovery heat at idle condition and the step-load condition.
Findings: Because the recovery of heat was about 1. 7 kW at idle condition, the effect of the EHRS on the warm-up performance was negligible. However, due to 17.2 kW of the recovery of heat at the stepload condition of T=140 Nm at N=2,400 rpm, the EHRS enabled to shorten the warm-up time by 548 s comparison that of the base engine.
Improvements/Applications: The fuel economy will be expected to be improved through an EHRS, which provides the improved combustion in the warm-up phase and a decrease in friction loss.

Keywords: *EHRS (Exhaust Gas Heat Recovery System); a Plate Heat Exchanger; Multi-Disciplinary Analysis; Gasoline Engine; Engine Warm Up.*

1. Introduction

The maximum achievable thermal energy for the modern conventional engine is about 30%, i.e., only 30% of the fuel energy in the engine is used to generate the power for driving vehicle. In particular,about 30% of thermal energy is wasted through the exhaust system in the form of the exhaust gas.The wasted heat is favorable due to the high energy level.In order to improve the fuel efficiency of the vehicle, it is necessary not only to optimize the efficiency of the powertrain itself, but also to adapt the EHRS(Exhaust gas Heat Recovery System) technology to utilize the waste heat discharged to exhaust system. [1-2] Two approaches are possible: direct use of the heat exchanger or indirect use of the exhaust heat with the heat storage. During the cold start of the vehicle, friction loss increases to the high viscosity at low temperatures such as engine oil and ATF (Automatic Transmission Fluid). The fast engine warm-up reduced the engine friction and the cylinder wall heat loss. So, the fuel economy expected to be improved through the fast warm-up technology, which is the recovery heat from the exhaust gas.[3]
Figure 1 shows the schematic diagram of the layout of the cooling system with theEHRS, which is installed between the catalyst and the center muffler to recover the exhaust heat by forcibly circulating the coolant until the engine warm-up. The ideal location of the EHRS is the position downstream of the catalyst, which keeps the coolant hose at a minimum length as shown in figure 1. The recovered heat can be directly used in the cooling system for warm-up andthe preheating ATF with the ATF warmer/cooler.[4]The EHRS shortens the warm-up time of the cooling system and lubrication system of the vehicle. The EHRStechnology is simple compared with other fuel efficiency enhancement technologies and can be effectively applied without changing or control logic of the base engine.

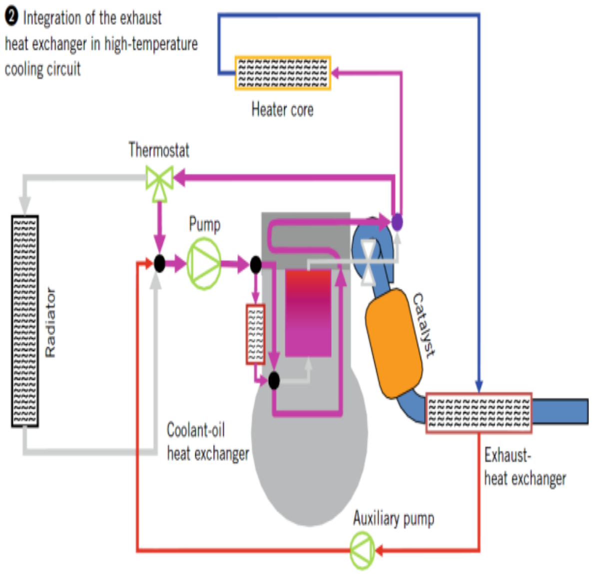


Fig. 1: Exhaust Gas Heat Recovery System4.

As the fuel economy is more and more important in the cold FTP-75(Federal Test Procedure 75) driving cycle, a number of researches have been conducted to improve the fuel economy during the cold start.Wenzel et al.[4]investigated the warm-up behavior for different testing cycles and the potential of the EHRS for coolant heating. They tested that the fuel consumption benefited of 2.1% for the WLTC (Worldwide Harmonized Light-Duty Test Cycle) and 3.9% for the FTP-75 driving cycle at -7°C ambient temperature.They reported that the fuel economy was improved with the EHRS, especially for testing at low temperatures. Park et al. [5] experimentally conducted the effects of warm-up performance of the gasoline engine with the circular flow typedEHRS. They showed that under engine high load condition, the remarkable heat recovery efficiency improvement was observed.Shin et al. [6] investigated the performance characteristics of the counter flow typed EHRS, such as warm-up, the exhaust noise and the back pressure of the for the gasoline engine. The warm-up period of the engine with the EHRS was shorted for the engine test conditions except at idle condition, although the back pressure wasslightly increased.

Model based approach has become essential to the new design and the evaluation for the EHRS, which is one of the vehicle thermal management systems. Lee et al.[7] investigated the effect of the cooling temperature on the fuel economy during warm-up period using the vehicle thermal model. They showed that the fuel economy of the vehicle with the EHRS improved by 7.3% at 24°C ambient temperature, and 20.1% at -6.7°C ambient temperature during the FTP driving cycle.Sahaet al. [8] performed the model based approach to design and optimize the thermal management system. They studied the effects of the various thermal management system, such as variable pump speed, variable coolant valve, variable active grille system and the control strategy on the fuel economy.

Most previous studies have focused on the circular flow typed EHRS. Since the EHRS itself increases the total weight of the vehicle, it is necessary to study for the EHRS with a plate heat exchanger. The objective of this paper is to investigate the effects of the design parameters of the EHRS with a plate heat exchanger on the warm-up performance of a gasoline engine.A plate heat exchanger was fabricated to more effectively recover the exhaust heat and was mounted the exhaust system of the gasoline engine. The warm-up behaviorsatidlecondition and stepload condition were analyzed by the engine dynamometer and the multi-disciplinary analysis.

2. Experimental setup and numerical method

2.1. Exhaust heat recovery system

Figure 2 shows the three-dimensional view of the EHRS, which consists a plate heat exchanger, the ducts for the exhaust gas, and the thermostat for the exhaust flap control.As the engine coolant at low temperature flows through the heat exchanger in the EHRS, the heat from the exhaust gas at high temperature is transferred to the coolant during cold start. It accelerates the engine warm-up. Since the thermostat blocks the exhaust gas flow path after the engine warm-up, the exhaust gasdoesn't circulate in the heat exchanger any more as shown in figure 2.It means that unnecessary heat recovery is not performed after the engine warm-up. As shown the figure, a plate heat exchanger is manufactured by stacking the heat transfer plates.The exhaust gas and the coolant paths are formed between the heat transfer plates.The heat exchanger in this study has 6 flow paths. The embossed design of the heat transfer plate, of which the material was SUS316L and the thickness was 0.4mm, was used to reinforce the strength between the pair of plates and enhance the heat transfer. It was designed and brazed to withstand the 10 bar of the burst pressure. In order to minimize the pressuredrop of the exhaust and the coolant in the EHRS, it has the I-flow typed cooling channel. Table 1 summarized the specification the plate heat exchanger of the EHRS.

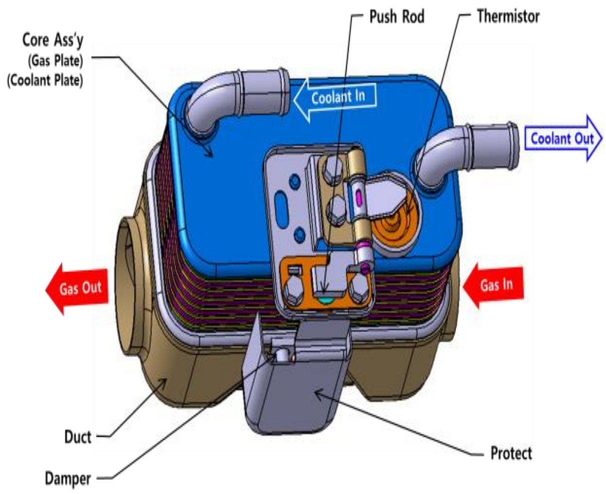


Fig. 2:.The EHRS with A Plate Heat Exchanger.

Table 1: Specification of the EHRS

Item	Exhaust gas	Coolant
Tube length (mm)	180	180
Tube cross section area (mm^2)	308	440
Tube wetted perimeter (mm)	183	186
No. of row (ea)	1	1
No. of tubes per row	6	6

2.2. Multi-disciplinary model

Multi-disciplinary analysis enables the model based approach for designing and investigating the thermal management system with the engine performance. The thermal model of a gasoline engine with the EHRS was shown in Figure 3.The thermal behaviors of the engine weresimulated by a commercial system simulation code, CRUISE^{TM} M, which enables to simulate the transfer of heat generated in the cylinder through the engine block, air, coolant, and oil circuits to the dedicated heat exchangers such as a radiator and an oil cooler. The model consists of sub-models which are an engine, a driver or a controller, and cooling circuits such as oil and coolant.[9]Most of all, it is necessary to accurately predict the rate of heat release from the engine combustion. In this work, the vibe function is used to approximate the actual heat release characteristics of an engine and is as follows: [10]

$$\frac{dx}{d\alpha} = \frac{\alpha}{\Delta\alpha_c} \cdot (m+1) \cdot y^m \cdot e^{-a \cdot y^{(m+1)}} \quad (1)$$

$$dx = \frac{dQ}{Q}, \quad y = \frac{\alpha - \alpha_0}{\Delta\alpha_c}$$

Where, Q is the total fuel heat input and x is the mass fraction burned. The crank angle α, the start of combustion $\alpha_0$and the combustion duration $\Delta\alpha_c$are 0°, 0°and 50°, respectively.The shape parameterm is 0.7 and vibe parameter ais6.901 in this work.
Figure 4 depicts the modeling of the EHRS in the hot side for the exhaust gas and cold side for the coolant. From the model of the heat transfer and pressure drop, the recovery heat in the EHRS can be simulated.

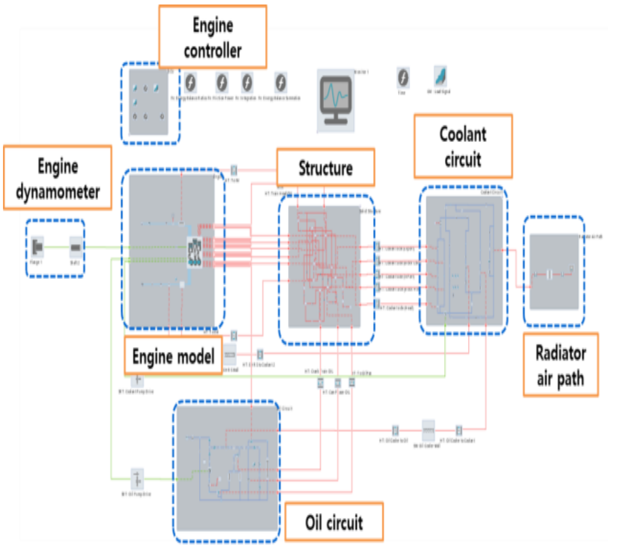


Fig. 3: Multi-Disciplinary Model of the Gasoline Engine with the EHRS.

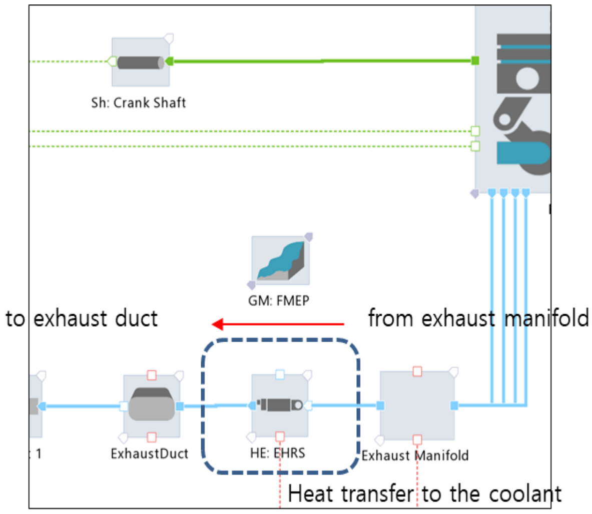


Fig. 4: Hot Side in the Engine Model.

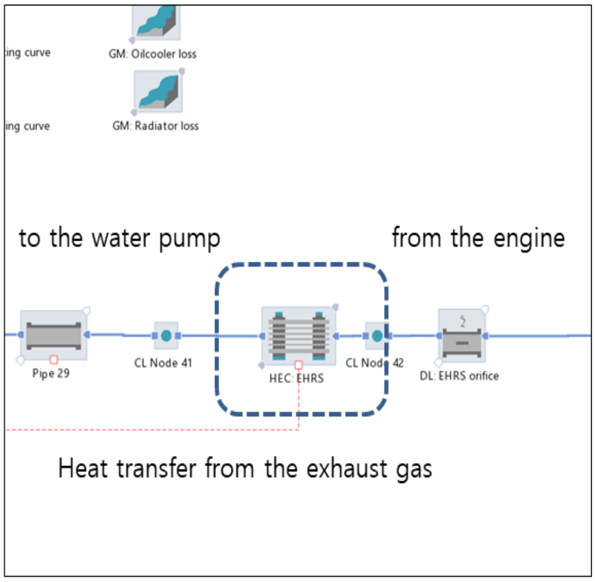


Fig. 5: Cold Side in the Coolant Circuit.

Figure 4.The modeling of the EHRS hot side and cold side

2.3. Experimental setup and test condition

Figure 5 shows the schematic diagram of the experimental setup of the GDI (Gasoline Direct Injection)engine with the EHRS. The type of the engine is the inline DOHC(Double Over Head Cam). The displacement of the engine is 2,359cc. The specification of the gasoline engine is summarized in Table 2. The load and the speed of the engine are controlled by 500HP of the dynamometer.The EHRS was installed at the behind of the catalyst and served as a silencer as well. The coolant inlet of the EHRS is directly connected the heater core outlet of the engine. So, the coolant flows simultaneously with the engine starting. When the engine is warm-up, the exhaust gas does not flow any more due to the exhaust gas flap which is controlled by the thermostat in the EHRS. To calculate the amount of heat recovery of the EHRS, the T-type Thermocouples and the turbine flow meters were installed to measure the coolant temperatures and the volume flow rates in the cooling system as shown the figure 5. The engine was tested at idlecondition and the step load condition of T=140 Nm at N=2,400 rpm, which is the representative operating point on the fuel economy driving cycle.The ambient temperature was 15°C.
The recovery of heatQ from the exhaust gas can be calculated as

$$Q = \dot{m} C_p (T_o - T_i) \quad (2)$$

Where, $\dot{m}$and $C_p$areare the mass flow rate [kg/s] and specific heat of the coolant [J/kgK], respectively. $T_0$is the outlet temperature [°C] and $T_i$is the inlet temperature [°C] of the coolant.

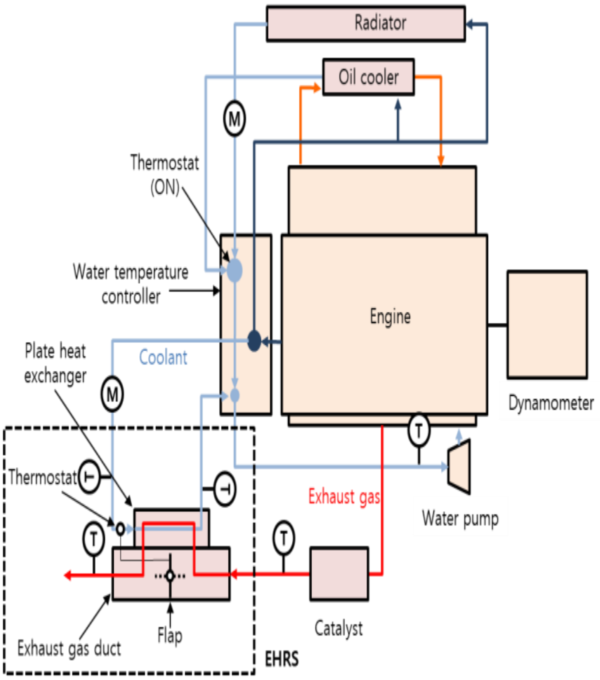


Fig. 5: Schematic Diagram of the Experimental Setup.

Table 2: Specification of the Engine

Item	Description
Type (Fuel System)	I4 DOHC (gasoline GDI)
Bore × Stroke(mm)	88.0 × 97.0
Displacement (cc)	2,359
Compression ration	11.3
Max. power (ps/rpm)	164/5,800
Max. torque (kg m/rpm)	22.7/4,250

3. Results and discussion

Figure 6 shows that the temperature characteristics of the EHRS inlet and outlet at idle condition. After the engine operation starts, the coolant starts to flow through the EHRS.The heat transfer occurs between the exhaust gas in hot side and thecoolant in cold side. The exhaust gas temperature gradually increases and becomes about 301°C and the coolant flow rate is 3.4L/min at 638s of the engine operating time. Due to the heat transfer to the coolant, the outlet temperature of the exhaust gas through the EHRS decreases by 220.4°Cin the experiment as shown in figure 6(b).Since the amount of wasted thermal energy to the exhaust system is small at idle condition, there is less the recovery heat available in the EHRS. In addition, the required heat capacity for the engine warm-up increased due to the EHRS made by the SUS316L material and the additional coolantin the extended coolant tube. The convective heat was transferred from the coolant tube to an ambient as well.

Figure 7 depicts the coolant flow rate through the radiator and the coolant temperature at the engine inlet.At idle condition, the recovery of heat is about 1.7kW from the equation (2).During the engine cold start, the coolant circulates inside the engine.The engine has a temperature controller with a thermostat, which senses the coolant temperature so that the engine can be maintained in the range of 80°C~82°C of desired point.When the coolant temperature at the engine inlet approaches 80°C, the coolant starts to flow through the radiator.Regardless of whether the EHRS is applied or not, the warm-up times of the engine are about 638s atidle condition as shown in figure 7(b).The effect of the EHRS on the warm-up performance of the engine is negligible at idle condition.

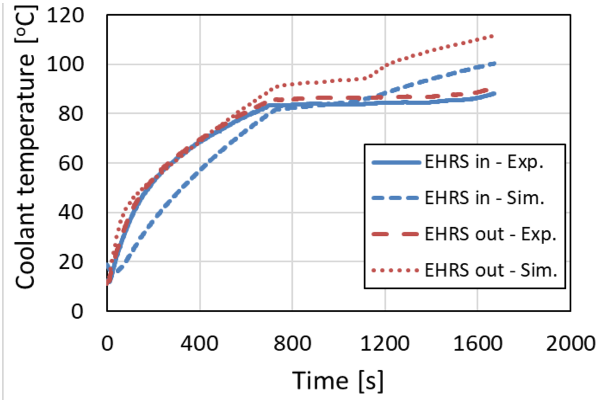
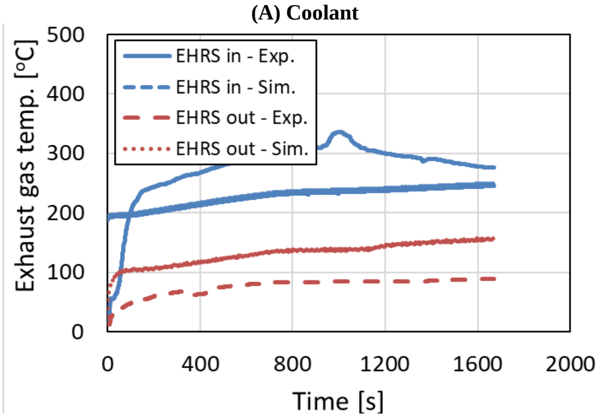
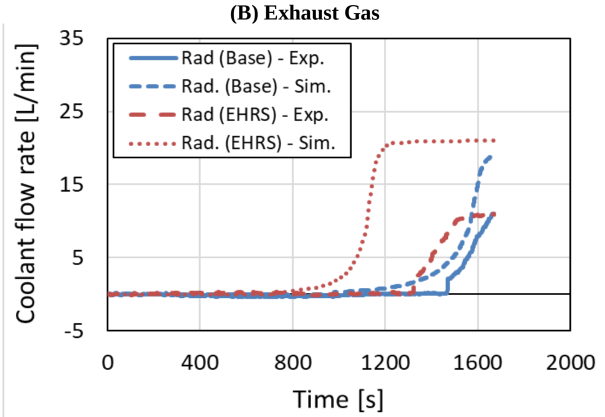


Fig. 6: Temperature Characteristics of the Ehrsat Idle Condition.

(A) Coolant



(B) Exhaust Gas



(C) Coolant Flow in Radiator

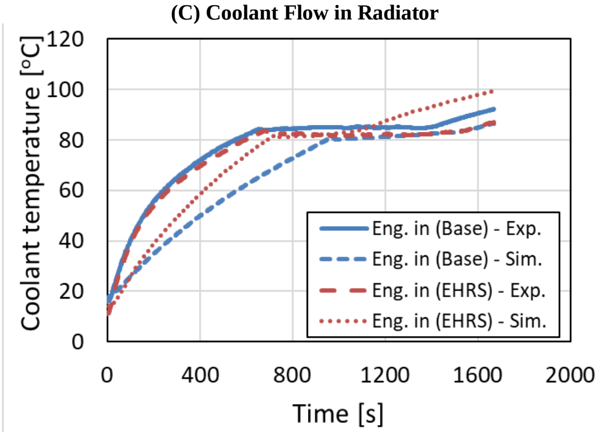


Fig. 7: Warm-Up Performance of the Engine with EHRS at Idlecondition.

Figure 8shows the coolant temperatures of the engine inlet and the radiator outlet at the stepload condition of T=140Nm at N=2,400rpm.As the engine load and speed increase, the wasted heat in the exhaust gas and the coolant flow rate rapidly increase as well. At 100s of the engine operation time, the coolant inlet temperature

in the EHRS is 84.9ºC and the coolant outlet temperature is 99.6ºC and is increased by 14.9ºC in the experiment.The coolant from the EHRS mixes with the coolant from the radiator at the water temperature controller and re-enters to the engine by the water pump as shown in figure 5. The exhaust temperature is 619.2ºC at inlet of the EHRS and is cooled by 412.1ºC at outlet of the EHRS.
The coolant flow rate of the radiator and the inlet temperature of the engine are shown in figure 9. At the engine step load condition, the recovery of heat is about 17.2kW.Unlike the engine idle condition, during the engine step load condition, the warm-up time of the engine with the EHRSis rapidly shortened from 638s to 90s.

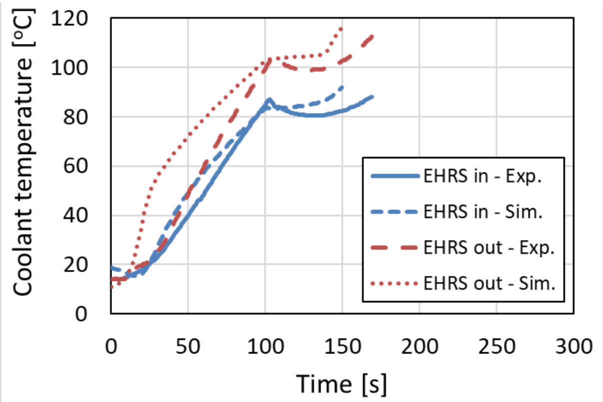


Fig. 8: Temperature Characteristics of the Ehrsat the Stepload Condition of T=140 Nm at N=2,400 Rpm.

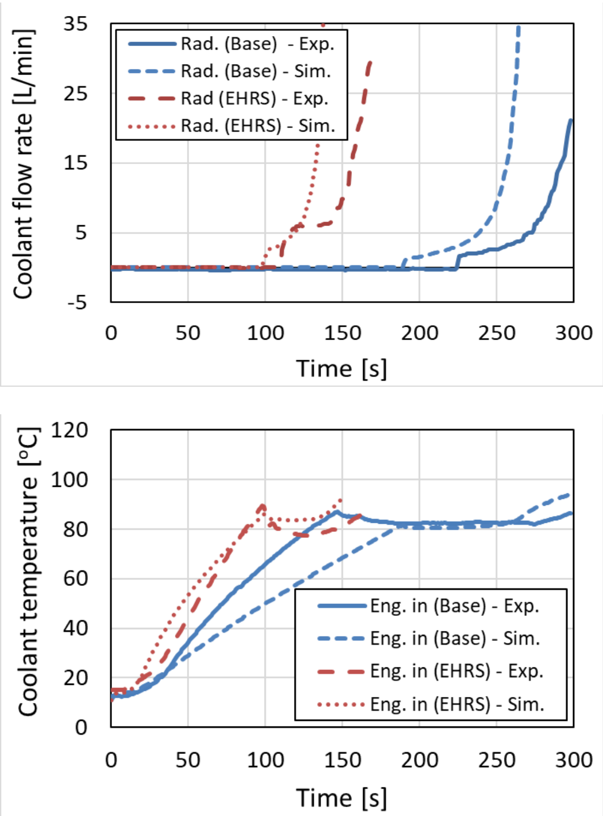


Fig. 9: Warm-Up Performance of the Engine with the EHRS at the Step load Condition of T=140 Nm at N=2,400 Rpm.

4. Conclusion

In this paper, the experimental study and multi-disciplinary analysis were carried out to investigate the effects of the EHRS on the warm-up performance of the engine, such as the coolant temperature, the exhaust gas temperature and the recovery heat at idle condition and the step-load condition.A plate heat exchanger was fabricated to more effectively recover the exhaust heat and was mounted the exhaust system of the gasoline engine. The warm-up performance behaviors at idle condition and stepload condition were tested by the engine dynamometer and simulated by the multi-disciplinary analysis.Because the recovery of heat was about 1.7kWat idle condition,the effect of the EHRS on the warm-up performance was negligible. However, due to 17.2kW of the recovery of heatat the stepload condition of T=140Nm at N=2,400rpm, the EHRS enabled to shorten the warm-up time by 548s comparison that of the base engine.

Acknowledgment

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