

Application of phase change materials to pre-heating of evaporator and pressure regulator of a gaseous sequential injection system

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ABSTRACT

The vehicle engines having gaseous sequential injection systems of liquefied petroleum gas (LPG) are operated on gasoline until the engine coolant reaches the required temperature because the heat of the engine coolant passing through the evaporator and pressure regulator (E&PR) is not enough to vaporize the LPG that is at liquid phase. Therefore, the fuel economy and the decreasing pollutant emissions emitted to the environment through use of LPG cannot be completely achieved at cold start of the engines. In this study, an E&PR that can store thermal energy was designed by using of phase change material (PCM) in order to overcome cold start problem of E&PR in vehicles operated with LPG. The thermal behavior of the E&PR with PCM was determined at idle operating conditions and the effects of using the E&PR surrounded with PCM on exhaust emissions (HC, CO) were examined. It was observed from the study that the E&PR with PCM can solve the cold start problem of the LPG powered engines. The E&PR surrounded with PCM could start the engine with LPG after the 15 h cooling period of the engine and LPG usage decreased HC and CO emissions by 17.32% and 28.71%, respectively.

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1. Introduction

In recent years, in order to reduce the environmental damage of automobiles and meet the stringent emission regulations, clean alternative fuels such as liquefied petroleum gas (LPG), natural gas (NG), and hydrogen (H) have been applied in automobiles in many countries [1]. LPG is well known as a clean alternative fuel for vehicles because it contains less carbon molecules than gasoline or diesel. Its higher ratio of carbon (C) to H reduces the amount of carbon dioxide (CO₂) and other non-regulated emissions, such as formaldehyde and acetaldehydes. LPG also has other many advantages such as high octane number, high combustion value, little carbon accumulation, easy storage, and low cost [2]. In an attempt to decrease air pollution and obtain fuel economy, several LPG engines have been developed for vehicles and have replaced various internal combustion engines. There are several types of LPG fuel supply system, ranging from gas vaporization with an open-loop control system to liquid injection with a closed-loop control system. Most commercially available LPG engines adopt a mixer type system, which supplies gas fuel into the intake air upstream of the throttle body with a vaporizer [1]. But, conventional mixer systems have problems for meeting stringent low emission regulations because of the difficulty in precise control of air fuel ratio [3]. The

gaseous sequential injection (GSI) system which is a LPG gas phase port injection system considered as one of the next generation fuel supply systems for internal combustion engines has reduced the problems of air–fuel ratio control in light and middle duty vehicles [4]. However, using LPG as fuel is not sufficient to achieve the emission target at cold start because the engine has the GSI system that cannot be operated on LPG until the engine coolant, which heats the evaporator and pressure regulator (E&PR) of LPG, reaches the required temperature.

Many researchers reported that 50–80% of hydrocarbon (HC) and carbon monoxide (CO) emissions are exhausted during the cold start before catalyst activation. Following the cold start condition, HC and CO concentrations generally drops and stabilizes after the first 2 min. [3,5]. For this reason, Euro III, Euro IV, Euro V and Federal Test Procedure (FTP) driving cycles for emission tests include cold start. This modified cold-start procedure is also referred to as the New European Driving Cycle or NEDC [4,6].

Numerous studies on various factors about engine combustion, engine control and aftertreatment have been carried out to reduce cold start emission [7–15]. Exhaust catalyst systems included among the technologies to decrease cold start emission are; thin wall catalysts, electrically heated catalysts, chemically heated catalyst, electrically initiate chemically heated catalyst, precatalyst method, catalyst surface control method, close-coupled catalyst system, and preheated catalytic converters by using phase-change materials which have been proved to be quite effective for meeting

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future emission regulations [16–25]. The other exhaust aftertreatment systems such as flow optimized exhaust manifolds and stainless steel exhaust manifolds are also effective methods [26,27]. In addition to aftertreatment technology, retarding spark timing, exhaust gas ignition system, heat exchanger method, electrically engine heaters and latent heat storage system for pre-heating of engine have been proved to reduce exhaust emissions very effectively [28–32].

A literature survey by the author showed that no published sufficient results on the effect of LPG usage on exhaust emissions at cold start in spark ignition engines with the GSI system. However, it is very important to know the effect of LPG usage on exhaust emissions and fuel economy at cold start. Therefore the engine having the GSI system should be operated on LPG at cold start in order to obtain fuel economy and the beneficial environmental impact expected from LPG. Development of new devices which allow GSI system of engine to be operated on LPG at cold start are an essential requirement especially for regions with a cold climate.

In this study, an E&PR that can store thermal energy was designed by the use of phase change material (PCM) in order to overcome the cold start problem of the vehicles operated with LPG. The development thermal energy storage device (E&PR surrounded with PCM) works on the effect of absorption and rejection of heat during the solid–liquid phase change of heat storage material ($\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$). The test engine could be operated on LPG at cold start by applying the E&PR surrounded with PCM at 4 °C temperature and 1 atm. pressure. The thermal behavior of the E&PR surrounded with PCM is tested at idle operating conditions and the effects of the E&PR surrounded with PCM on the exhaust emissions (HC, CO) of cold start were examined.

2. Experimental set-up and procedure

2.1. The gaseous sequential injection system

The engine of the vehicle used in experiment was modified with a GSI to be operated on gasoline and LPG. The engine is a spark ignition, four-stroke, four cylinder, fuel injection, water-cooled engine and the details are given in Table 1. The GSI system consists of the following parts: A fuel tank, safety shut-off valves, injectors, an electrical control module (ECM), and an E&PR. The E&PR was revised by using PCM in order to store thermal energy.

The vehicle motors having GSI systems can be operated on gasoline and LPG. But it must be operated on gasoline at cold start until the engine coolant, which heats the E&PR, reaches the required temperature because the heat of the engine coolant passing through the E&PR is not enough to vaporize the LPG at liquid phase.

It is important for the injector performance and to obtain adjusted air fuel ratio in which the LPG is fully vaporized when it is injected into the engine cylinders. Therefore, the LPG which is taken from the tank in a liquid state is fully vaporized in the E&PR by decreasing pressure. LPG is also heated by allowing the coolant flow through the E&PR and thereby heating up the metal surrounding the LPG in order to make sure that all LPG fuel will vaporize, thus preventing the E&PR to freeze up.

To make it possible to inject the fuel into the inlet manifold easily, the pressure in the inlet manifold must be lower than the pressure in the tubing between E&PR and injectors. For the control of the injection process, the difference between these two pressures must be a specified value. When the fuel flows from the E&PR to the injectors, pressure is adjusted to a specific value relative to the inlet manifold pressure by the E&PR. In the GSI used in the test engine, the pressure difference was arranged at 100 kPa.

Table 1
Specifications of the test engine.

Trademark and model of vehicle	Renault Clio RTA 1.4i 2000
Engine type	4 Stroke, Overhead-Camshaft, 8 valves
Fuel injection system	Multi point sequential injection with electronic control
Type of engine cooling	Water cooling
Number of cylinder	4
Firing order	1-3-4-2
Diameter of cylinder	75.8 mm
Stroke length	77 mm
Displacement	1390 cm ³
Compression ratio	9.5:1
Maximum engine speed	5950 rpm
Maximum engine power	55.9 kW @ 5500 rpm
Maximum engine moment	114 N m @ 4250 rpm

2.2. Selection of phase change materials

In the automotive industry, PCMs are used in cooling of engines [33], thermal comfort in vehicles [34], pre-heating of catalytic converters [23–25], pre-heating of engine [30–32] and other applications in internal combustion engines [35,36]. While selecting a suitable PCM; there are some criteria such as high latent heat of phase change, appropriate of the working temperature range, high thermal conductivity at solid state, high specific heat capacity at liquid state, good chemical stability and low vapor pressure at working temperature ranges, high density, inflammability, little volume variation during solidification, minimum thermal storing losses, environment friendly and reasonable price [37–39].

For the desired-temperature range, the following phase change materials are the most suitable for the E&PR stored thermal energy: Sodium Phosphate Dibasic Dodecahydrate ($\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$), Sodium Sulfate Decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), Calcium Chloride Hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), Lithium Nitrate Trihydrate ($\text{LiNO}_3 \cdot 3\text{H}_2\text{O}$), Zinc Nitrate Hexahydrate ($(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$).

In this study $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ was chosen as phase change material for designed an E&PR stored thermal energy because its working temperature range is suitable, its heat of fusion is high and it is also cheap and abundant. The function of PCM is supposed to recover the energy of hot engine coolant through E&PR surface during a driving cycle and to restore this energy to LPG for vaporizing at the next cold start. The properties of $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ and some selected phase change materials which can be used as an alternative in the E&PR for thermal energy storage are given in Table 2.

2.3. Design of the E&PR surrounded with PCM

Thermal energy storage devices should have high heat capacity, minimum thermal storage losses, comparatively small dimensions and mass, vibration resistant design to satisfy engine operating conditions and compatibility with the environment [30]. Therefore, the E&PR stored thermal energy with PCM has to provide, on the one hand, the maximum possible heat transfer contact area between the coolant, PCM materials and LPG to enable a high heat transfer rate among them and, on the other hand, the minimum external surface area to reduce the heat losses to the surroundings. Different configurations for the E&PR surrounded with PCM can be constituted and the superior configuration can be determined by examined effects of the ratio between the interface and surface area of alternative configuration. But in this study an E&PR stored thermal energy with PCM was designed as basic and useful device to provide high heat capacity, minimum thermal energy storage losses and compatibility with the conditions of the engine

Table 2

Basic properties of the selected phase change materials which can be applied in the E&PR as thermal energy storage materials.

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m ³)
Calcium Chloride Hexahydrate (CaCl ₂ ·6H ₂ O)	29	187.5	0.538	1560
Lithium Nitrate Trihydrate (LiNO ₃ ·H ₂ O)	30	n.a.	n.a.	296
Barium Hydroxide Octahydrate (Ba(OH) ₂ ·8H ₂ O)	48	265.7	0.653	1937
Zinc Nitrate Hexahydrate ((NO ₃) ₂ ·6H ₂ O)	36	147	0.464	147
Sodium Carbonate Dodecahydrate (Na ₂ CO ₃ ·12H ₂ O)	32–36	246.5	n.a.	1442
Sodium Sulfate Decahydrate (Na ₂ SO ₄ ·10H ₂ O)	32.4	254	0.544	1485
Sodium Hydroxide (NaOH)	64.3	227.6	n.a.	1690
Sodium Phosphate Dibasic Dodecahydrate (Na ₂ HPO ₄ ·12H ₂ O)	36	265	n.a.	1522

n.a.: not available.

operation and the environment for applying experiment. It was not struggled to minimize dimensions and mass of the E&PR.

Configuration of system consists of a common cylindrically shaped E&PR, a PCM jacket, polycarbonate envelope and a thermal insulation. The E&PR has one stage which vaporize the LPG fuel and to control the pressure. The design of the experimental thermal energy storage device (E&PR surrounded with PCM) used during the testing procedure is given in the Fig. 1. The parts of the experimental thermal energy storage system are; insulation (1), envelope (2), PCM (3), E&PR (4), LPG channel (5), drain plug (6), coolant inlet

pipe (7), coolant outlet pipe (8), coolant channels (9), LPG outlet as gas phase (10), solenoid valve (11), LPG inlet as liquid phase (12), LPG adjustment lever (13). The parameters are; R diameter of the thermal energy storage envelope, S height of the thermal energy storage envelope, r diameter of the E&PR, a and b thickness of thermal insulation, c and d thickness of envelope, x , y , z , and q spaces between internal surface of envelope and external surface of the E&PR. The thickness of PCM layer between the E&PR and the envelope changes from 9 mm to 15 mm according to the shape of the E&PR. The height and diameter of the E&PR surrounded with PCM is 100 mm and 132.5 mm, respectively.

The mass of PCM and thermal energy (heat of fusion) stored by the E&PR surrounded with PCM are 1.2 kg and 318 kJ, respectively. Thermal energy stored by the E&PR surrounded with PCM can be increased by using different PCMs having high heat of fusion under the condition of constant dimensions. Thermal energy can be also increased by increasing dimensions of the E&PR surrounded with PCM for heavy duty engine. The main characteristics of the E&PR surrounded with PCM are given in Table 3.

2.4. Description of experimental system and procedure

The basic scheme for the connection of E&PR surrounded with PCM to the cooling system of the engine and GSI system is shown in Fig. 2. During heat storage period, engine is running on gasoline or LPG and coolant is circulated through the E&PR, the water jacket of the engine and heater by the water pump of engine. If the thermostat is open, the coolant also flows through the radiator. During the heat conservation period, engine is switch off and the coolant inlet–outlet valves of the E&PR are closed to prevent convection heat transfer with fluid motion. During heat recovery period, the coolant inlet–outlet valves are closed and coolant is not flowed through the E&PR so that the PCM does not lose thermal energy by heating the engine coolant. The thermal energy of PCM is only consumed by evaporation of LPG.

Experiments were carried out in storage (engine is running on gasoline or LPG and coolant is circulated through the E&PR), conservation (engine is switch off and the coolant inlet–outlet valves

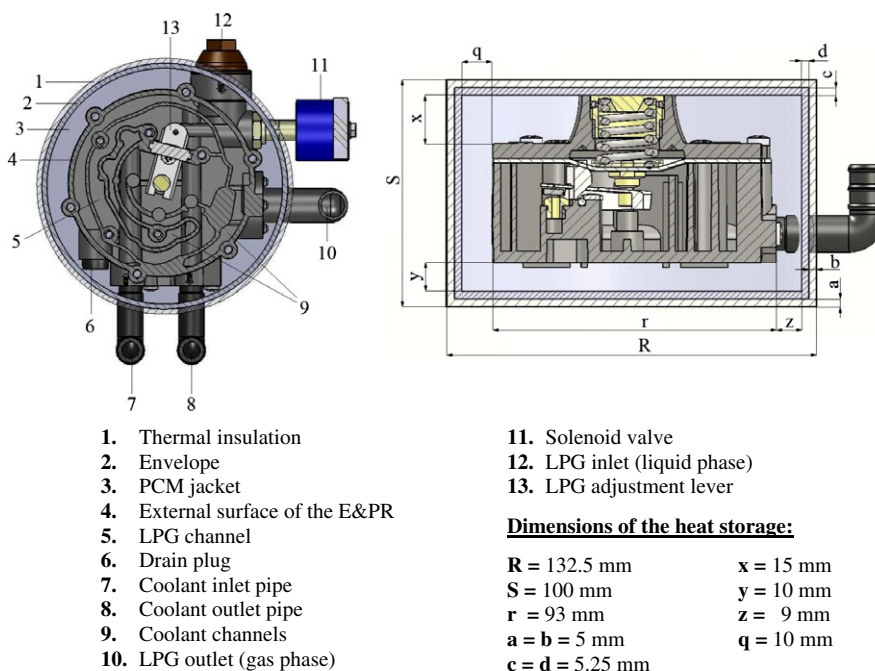


Fig. 1. Design of the thermal energy storage device (E&PR surrounded with PCM).

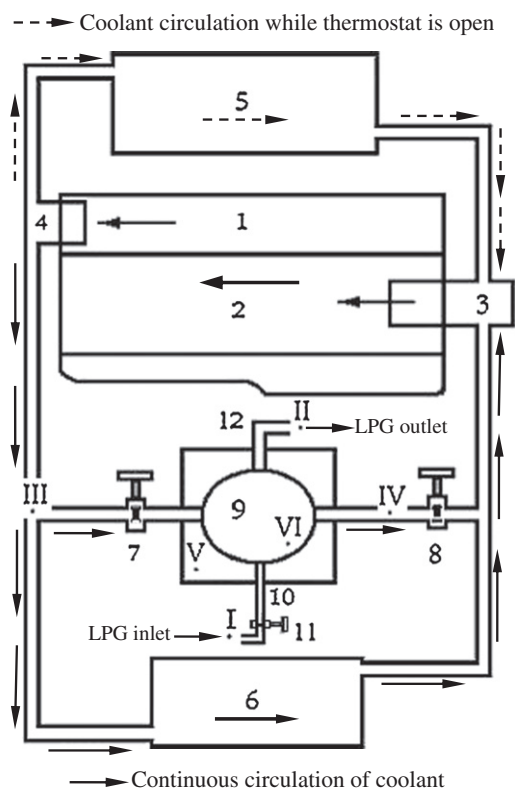
Table 3
Main characteristics of the E&PR surrounded with PCM.

Mass of PCM used in surrounding of the E&PR	1.2 kg
Thermal energy (heat of fusion) stored by the E&PR with surrounded PCM	318 kJ
Dimensions of the E&PR surrounded with PCM (diameter × height)	132.5 × 100 m

of the E&PR are closed) and recovery (engine is running on LPG and the coolant inlet–outlet valves of the E&PR are closed) periods of the E&PR surrounded with PCM when the temperature and pressure of environment are 4 °C and 1 atm, respectively. The temperatures of LPG inlet–outlet, engine coolant inlet–outlet, PCM and E&PR were measured by using Ni–NiCr type thermocouples and a temperature measuring instrument. The temperature of catalytic converter was also measured. CO and HC emissions of engine fueled with gasoline and LPG at cold start were measured before and after catalytic converter by an engine emission analyzer. The emission and the temperature measurements in storage and recovery period were made with the engine at idle. All measurement systems were calibrated and the accuracies of the measurements are shown in Table 4. Each experiment was replicated three times to obtain a sensitive value.

2.5. Properties of fuels

LPG includes saturated hydrocarbons, propane (C₃H₈) and butane (C₄H₁₀), which can be stored separately or as a mixture. The



1. Cylinder block cover
2. Cylinder block
3. Coolant pump
4. Thermostat
5. Radiator
6. Heater
7. Coolant inlet valve
8. Coolant outlet valve
9. E&PR with PCM
10. LPG inlet (liquid phase)
11. Solenoid valve
12. LPG outlet (gas phase)

Fig. 2. Location of the E&PR surrounded with PCM and thermocouples on the system (I, II, III, IV, V, and VI show temperature measurement points).

Table 4
The range and accuracy of the measurements.

Measurement	Range	Accuracy
Temperatures	0–1000 °C	±0.1 °C
HC	0–10000 ppm	±1 ppm
CO	0–10%	±0.01%

composition of LPG used as an engine fuel varies widely from one country to another, depending on the cost and availability of the fuel in relation to essential fuels, notably petrol and diesel. The climate condition of countries also affects on the preference of LPG composition. The LPG utilized in the engine tests consist of 50% propane and 50% butane. Physical and combustion properties of propane, butane and gasoline fuel used in this study are listed in Table 5.

3. Results and discussion

3.1. Heat storage period

Temperature of the E&PR surrounded with PCM was measured from six different points. First point is before the LPG inlet valve that is controlled by LPG electronic control unit (ECU) and opened when the temperature of regulator reaches to 30 °C, second point is on the outlet of LPG from E&PR, third point is before the coolant inlet valve, fourth point is before the coolant outlet valve, fifth point is on the PCM between external surface of the E&PR and internal surface of the envelope, and the sixth point is on the coolant channel of the regulator.

Temperature variation of coolant inlet–outlet and PCM in charge period (engine is running on gasoline) according to time is shown in Fig. 3. There is no LPG flow to the system at this condition and the heat of the engine coolant is only stored by the PCM. According to measurement results, average temperature of inlet valve of the E&PR is more than outlet temperature in charge period. Inlet temperature of the E&PR has a tendency to increase until it reaches to the stable temperature. Outlet temperature of the coolant initially increases linearly and the difference between inlet and outlet temperatures of coolant is so small until the temperature of PCM reaches to the phase change temperature (36 °C, about 450 s). The heat convection that causes this difference increases the sensible heat of the PCM. After the PCM starts to phase changing, the coolant inlet–outlet temperature difference increases for the reason that high amount of heat is stored by the PCM as latent heat. At the end of this period, the difference between inlet and outlet temperatures starts to decrease until the coolant reaches to the stable temperature. The temperature of PCM initially increases linearly until its melting temperature then its temperature approximately remain constant during the phase changing (about

Table 5
Physical and combustion properties of fuels.

Property	Gasoline	LPG	
		Propane	Butane
Liquid density, kg/m ³	765	509	585
Calorific value, MJ/kg	44.04	46.34	45.56
Boiling point, °C	30–225	–42	–0.5
Auto ignition temperature, °C	257	510	490
Flame temperature, °C	1720	1980	1775
Combustion rate, m/s	0.35	0.4	0.4
Stoichiometric air/fuel, kg/kg	14.7	15.8	15.6
Lower flammability limit, vol.%	1.3	2.1	1.5
Upper flammability limit, vol.%	7.6	9.5	8.5
Octane number	95	111	103

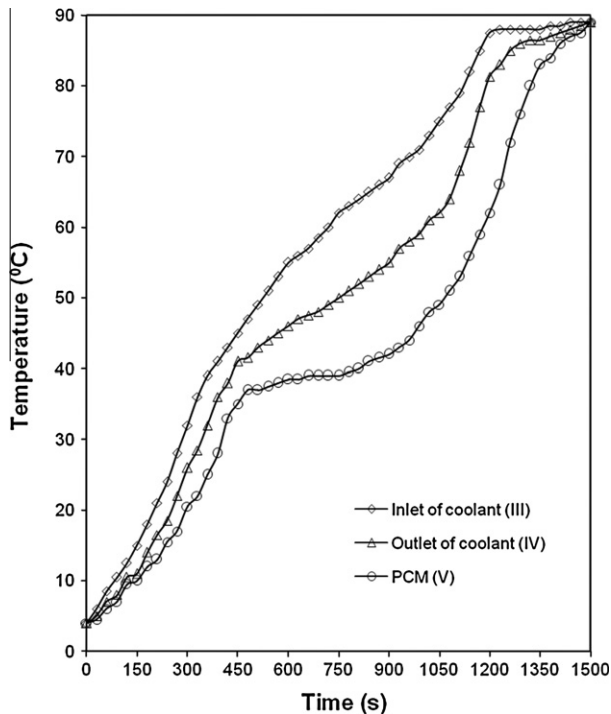


Fig. 3. Temperature variation of coolant inlet–outlet and PCM of the E&PR in heat storage period (engine is running on gasoline).

450 s) and after the this duration its temperature increases linearly again until its temperature reaches the engine stable temperature. So it can be said that the phase changing time of the PCM is by 7.5 min and the heat storage time of the E&PR surrounded with PCM is by 15 min when the engine is running on gasoline.

Temperature variation of coolant inlet–outlet, LPG inlet–outlet and PCM in charge period (engine is running on LPG) according to time is shown in Fig. 4. In this period, engine is running on gasoline first and all valves (LPG and coolant) of the E&PR are closed. Once the temperature of coolant reaches 30 °C, coolant valves are opened and the engine is starts to run on LPG fuel under the control of ECM of GSI system. LPG that enters the system as liquid is evaporated by the E&PR and carried to the fuel rail. Temperature variation of coolant inlet–outlet and PCM in this period shows the similar tendency to that of gasoline. However, the latent heat of evaporation absorbed by the LPG passing through the E&PR causes the PCM to get warm later and liquefaction of PCM to get more time. Completely melting of the PCM and storing of the required latent heat in the E&PR surrounded with PCM take by 600 s. LPG inlet temperature doesn't change while outlet temperature increases along with the charge period until it reaches to the stable temperature (about 30 °C). The coolant outlet temperature also decreases a little due to absorption of latent heat of PCM. Finally, it can be said that the phase changing time of the PCM is by 10 min and the charging time of the E&PR surrounded with PCM is by 18 min when the engine is running on LPG.

3.2. Heat conservation period

In this period, the E&PR was heated up to 90 °C by the coolant of running engine. Then the engine was stopped and the E&PR was allowed to cool down under the hood of engine at 4 °C ambient temperature. The engine hood and coolant inlet–outlet valves of the E&PR were kept closed along the experiment. Temperature variation was measured at each 30 min intervals for determining the temperature variation within the heat conservation period.

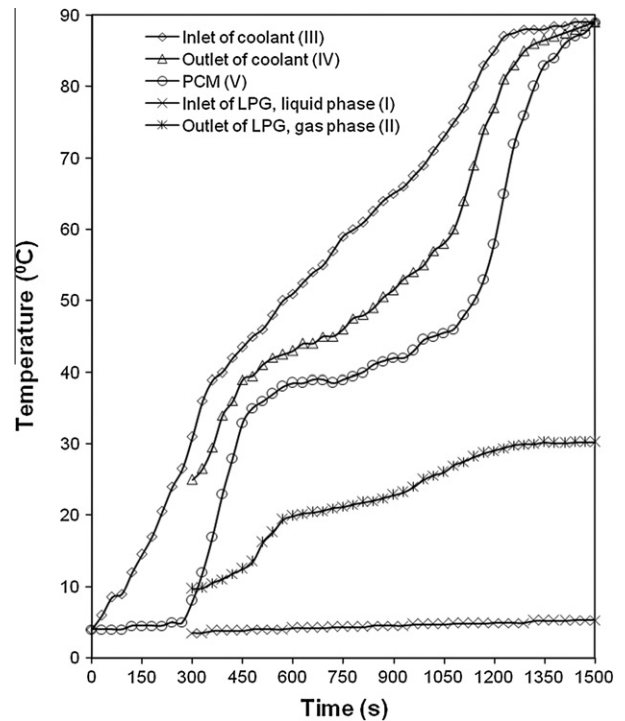


Fig. 4. Temperature variation of coolant inlet–outlet, LPG inlet–outlet, and PCM of the E&PR in heat storage period (engine is running on gasoline first, then LPG).

Temperature variation of the E&PR with and without PCM according to time is shown in Fig. 5. It is seen that the E&PR without PCM cools down immediately once the engine is stopped and the temperature of the E&PR without PCM decreases under the working temperature within by 200 min. But the E&PR surrounded with PCM cools slower than the E&PR without PCM and the temperature of E&PR surrounded with PCM decreases to the phase change temperature (36 °C) in by 480 min. It is also seen that when the temperature of E&PR reaches to the phase change temperature, decrease in its temperature is slowed down by means of the high latent heat of the PCM. Temperature of E&PR decreases from phase change temperature to its lowest working temperature (30 °C) in by 330 min. Therefore, it can be said that the temperature of E&PR decreases from the engine stable temperature to the lowest working temperature in by 810 min. In this case, engine can be started directly with LPG in 13.5 h waiting duration which is heat conservation period. Since at the lowest working temperature, PCM could not provide latent heat any more, the E&PR with PCM may not be able to vaporize LPG at this point. Therefore, the actual effective period of E&PR with PCM could be shorter than 13.5 h. But, the heat conservation period can be increased with better insulation.

3.3. Heat recovery period

In Fig. 6, temperature variation of coolant inlet, LPG inlet–outlet and PCM of the E&PR in heat recovery period is seen. The E&PR that stored heat with the latent heat of the PCM, was left to cool down at 4 °C ambient temperature for 12 h. After this duration the test engine was started directly with LPG without any other heat source (coolant inlet–outlet is closed). LPG passing through the E&PR surrounded with PCM absorbs heat from the PCM to be able to vaporize.

Heat required for evaporation of LPG is provided from the latent heat of PCM used in the E&PR for 500 s. Temperature of coolant reaches to the lowest working temperature of E&PR in 300 s which

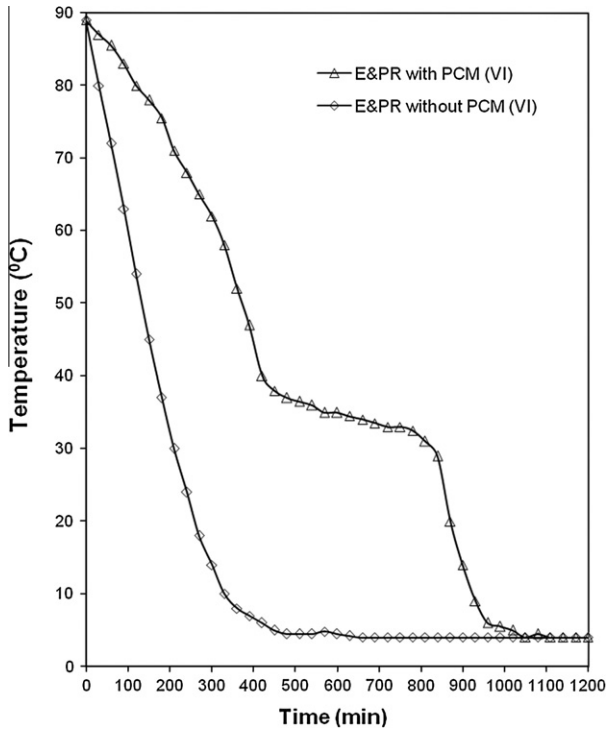


Fig. 5. Temperature variation of the E&PR with and without PCM in heat conservation period (engine is switch off and the coolant inlet-outlet valves are closed).

is lower than the period in which PCM provide heating. Therefore the E&PR surrounded with PCM can be used as a new device for the solution of cold start problem in the GSI systems and it ensures that the engines can start directly with gas phase of LPG.

3.4. Hydrocarbon (HC) emission

Test engine has a catalytic converter and exhaust emission measurements were made with the catalytic converter. Under normal operating conditions, catalytic converters appear to be the most effective means of reducing air pollution from internal combustion engines. The conversion efficiency, however, declines very steeply for temperatures below by 250 °C and is practically zero during the starting and warming-up period. This variation is shown clearly in Figs. 7 and 8. The converter temperature of gasoline usage is higher than that of LPG usage. The coolant temperature of gasoline fuel usage reaches the regime temperature just before that of LPG usage. Since this temperature difference is too small, average values of temperatures are plotted in the figures.

In Fig. 7, the values of HC emission after and before catalytic converter on gasoline and LPG operations according to the temperature variation of engine coolant and converter are seen. HC emission decreases with increasing temperature of engine coolant on both gasoline and LPG fuel usage. HC emissions of gasoline fuel at before and after catalytic converter are higher than that of LPG fuel for all warming up period. HC emission after the converter drops down rapidly when the converter reaches to active working temperature (280 °C in 350 s). Converter application on the engine when using gasoline fuel decreases HC emission by 16.28% during warming up period for 1000 s. LPG fuel usage decreases HC emission by 13.74% with respect to measurement result before converter. This reduction grows up to 33.60% with respect to measurement result after converter. So after cooling duration (12 h), using of LPG decreased HC emissions by 17.32% with respect to measurement result after converter at using gasoline fuel.

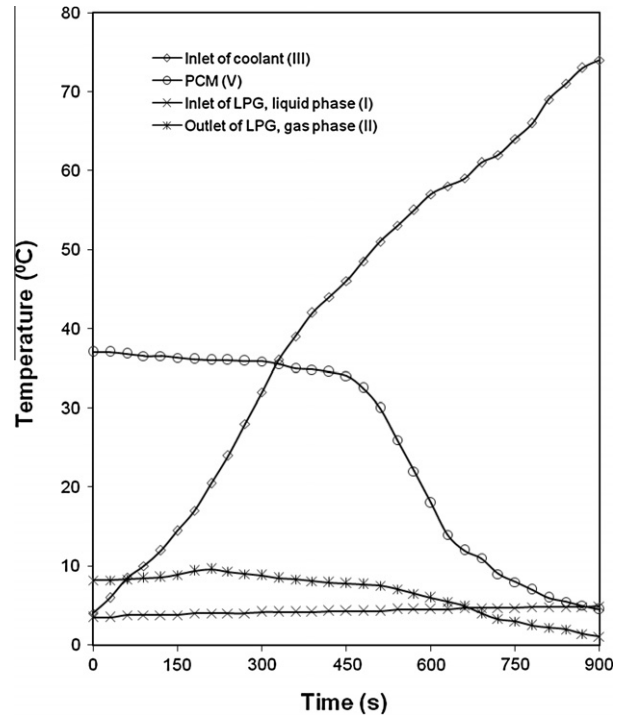


Fig. 6. Temperature variation of coolant inlet, LPG inlet-outlet, and PCM of the E&PR in heat recovery period (engine is running on LPG and the coolant inlet-outlet valves are closed).

Finally, starting the engine directly with LPG by means of the E&PR surrounded with PCM provides an important improvement on HC emission level emitted from the test engine during the warming up period.

3.5. Carbonmonoxide (CO) emission

The values of CO emission after and before catalytic converter on gasoline and LPG operations according to the temperature

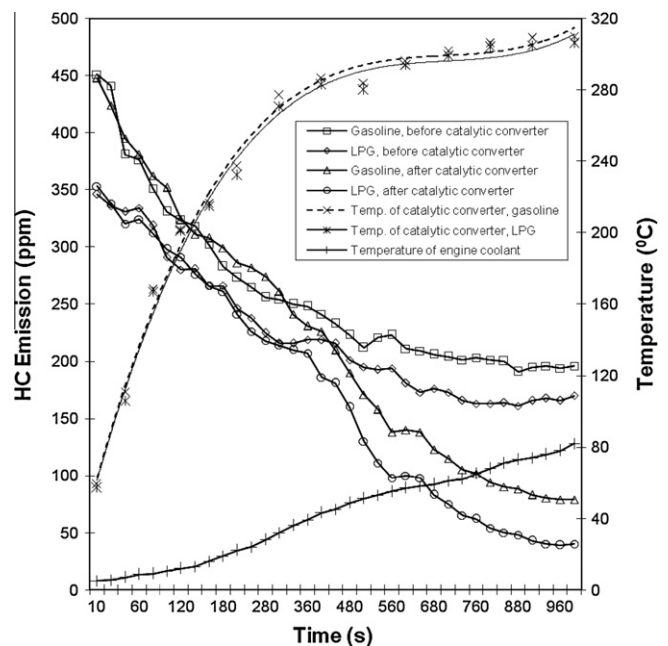


Fig. 7. HC emission variation of engine with respect to the temperature variation of engine coolant and converter.

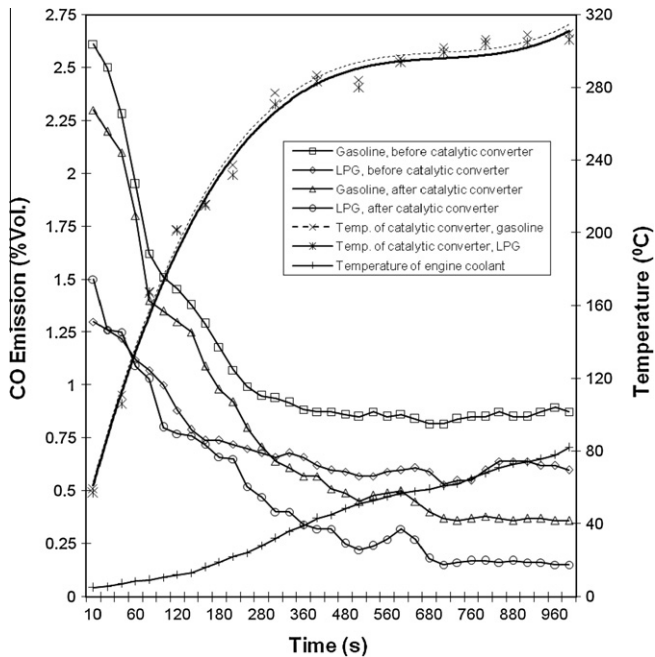


Fig. 8. CO emission variation of engine with respect to the temperature variation of engine coolant and converter.

variation of engine coolant and converter are plotted in Fig. 8. The variation of CO emission gives similar tendency to that of HC emission. CO emission on both gasoline and LPG fuel usage reduces with increasing temperature of engine coolant pending by 30 °C (in about 300 s). However, CO emission becomes stable after the engine coolant temperature reaches to by 30 °C. CO emission after the converter drops down rapidly when the temperature of converter reaches to the active working temperature (230 °C in 200 s). During the all warming up period, CO emission of LPG fuel is lower than that of the gasoline fuel for before and after catalytic converter. Converter application on the engine when using gasoline fuel decreases CO emission by 29.54% during warming up period for 1000 s. The decrease of CO emission with using LPG fuel is higher than that of HC emission. Using of LPG fuel decreases CO emission by 33.77% with respect to measurement result before converter. This reduction grows up to 58.25% with respect to measurement result after converter. Thus after cooling duration, using of LPG decreased CO emissions by 28.71% according to measurement result after converter at using gasoline fuel. It can be said that starting the engine directly with LPG by means of the E&PR surrounded with PCM has more advantages in terms of CO emission during the warming up period.

The application of E&PR with PCM increases the weight of vehicle due to the weight of PCM, thermal insulation, envelope, and inlet and outlet valves of coolant. A well designed E&PR with PCM increases the weight of vehicle a little. The increase in weight of vehicle may increase the emission of HC and CO slightly. For determination of increase in the emissions of HC and CO owing to the increase in weight of vehicle, a new detailed study should be carried out for various kinds of vehicles.

4. Conclusions

In this study, to solve the cold start problem of E&PR in vehicles operated with LPG, an E&PR that can store thermal energy was designed by using of PCM. The thermal behavior of the E&PR surrounded with PCM was determined as tested at idle operating conditions and the effects of the E&PR surrounded with PCM on

the exhaust emissions (HC, CO) were examined. $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ was used as phase change material. Developed experimental sample of thermal energy storage with PCM (E&PR surrounded with PCM) can store 318 kJ. The E&PR was mounted on the cooling system of engine and experiments were made at 4 °C temperature and 1 atm pressure.

Charging times of the E&PR surrounded with PCM when the engine is running on gasoline and LPG are by 15 min and 18 min, respectively. Heat conservation time of the E&PR is 810 min (13.5 h). The E&PR surrounded with PCM could start the engine with LPG after the 13.5 h cooling duration of the engine, while the temperature of the E&PR without PCM drops below the working temperature of engine with LPG in 3 h under the same conditions. The time (about 500 min) in which the E&PR surrounded with PCM provides the needed heat from the latent heat of PCM for evaporation of LPG is longer than the time (about 300 min) during which coolant temperature reaches to the lowest working temperature. Therefore the E&PR surrounded with PCM can be used as a new device to the solution of cold start problem in the GSI systems and it ensures engines to start directly with gas phase of LPG.

LPG usage at cold start is effective on air pollution originated from internal combustion engine. After cooling duration, using of LPG decreased HC and CO emissions by 17.32% and 28.71%, respectively. Finally, by the use of the developed thermal energy storage device (E&PR surrounded with PCM), the fuel economy expected from LPG can be enhanced and the pollutants emitted to the environment can be decreased.

Following this study, effects of different dimensions and configurations for the E&PR surrounded with PCM and effects of different PCMs having high heat of fusion and compatible operating temperature should be examined. Additionally, the increase in the emissions of HC and CO owing to the increase in weight of vehicle with application of E&PR with PCM should be investigated by a new detailed study for different vehicles. Moreover, the more uniform temperature during the operation of the E&PR surrounded with PCM may reduce the stress on the diaphragm of the E&PR and may extend its service life. Hence this effect should be also examined.

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