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Applying chemical heat storage to saving exhaust gas energy in diesel engines: Principle, design and experiment

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ABSTRACT

Thermal energy storage has become more and more important to improving the overall efficiency of energy systems by utilising the wasted energy. This study was aimed to develop a chemical heat storage (CHS) system using magnesium hydroxide ($Mg(OH)_2$) and its dehydration and hydration reactions to recover the thermal energy wasted by the exhaust gases in internal combustion (IC) engines. Experiments were conducted on a Diesel engine (D1146TI) to estimate the percentage of exhaust gas energy stored by CHS technology in the heat storage process. In this process, at 80% engine load, 61.4% of chemical material reacted and 5.05% heat energy of exhaust gas was stored in an hour. The percentage of the stored exhaust gas energy decreased with the engine loads. In the heat output process, in one of the proposed applications, the engine intake air was heated with the stored energy by hydrating MgO when the temperature of the inner wall of the reactor (T_6) increased from 45 °C to 86.4 °C. The experimental results show that at the ambient temperature 23 °C, the intake air can be heated to the temperature 5.7 °C-17.3 °C higher than the ambient temperature. The applications of CHS to heating the engine, lubricant or batteries in hybrid vehicles are proposed.

1. Introduction

Utilizing the wasted energy is one of the important strategies for addressing the current issue of sustainability by increasing the overall efficiency of the engine. Internal combustion (IC) engines have been widely used in many fields, such as transportation, construction or agricultural sectors. However, a significant amount of fuel energy has to be lost as wasted heat through exhaust gas. Some solutions to cover exhaust gas energy have been adopted including the thermoelectric generation (TEG) [1,2], exhaust gas recirculation system (EGR) [3] and heat exchangers [4,5]. However, the solutions convert and use the heat energy of exhaust gas instantaneously and may not be applicable in the situations which require to keep the stored energy until it is needed. Different from the instantaneous energy conversion systems, thermal energy storage (TES) that are applying in many fields, especially in concentrating solar power plant [6] or in the building [7] can store the energy until it is used.

Sensible, latent and chemical heat storages (CHS) are classified as TES. Sensible heat storage systems store heat energy based on the temperature changing of solid or liquid material. In the latent heat storages systems, the heat energy is stored in the latent heat of a phase change material. Different from the physical TES systems above, CHS systems store and release heat energy through the reversible reaction of chemical material [8]. As the chemical products of CHS system are stored separately at the ambient temperature, the stored energy can be retained for a long time with small heat loss [9]. However, the structure of a CHS system is more complex than that of a physical heat storage system, resulting in higher initial cost [10].

CHS systems have been applied to storing the solar energy for domestic hot water, air-conditioning [8], and heat energy in the thermal power plant [11]. However, applying CHS to IC engines is still new. The research of Kabushiki Kaisha Toyota Jidoshokki [12] was the first one to propose the application of CHS to recovering exhaust gas energy to heat the catalyst in IC engines.

In the present study, a new CHS system consisting of a reactor with $Mg(OH)_2$ as the initial chemical material has been developed and investigated to recover the exhaust gas energy of a diesel engine. The experiments were conducted to estimate the performance of the CHS system in the heat storage process at various engine operating conditions. In the heat output process, the stored energy was used to heat the engine intake air, aiming to extend this application to other heating required in IC engines and hybrid vehicles.

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Abbreviations

CHS	Chemical heat storage
IC engine	Internal combustion engine
TEG	Thermoelectric generation
EGR	Exhaust gas recirculation
EG	Expended graphite
EM8block	the compound of Magnesium hydroxide and Expanded graphite

Nomenclature

M_{H_2O}	Mole mass of the water (g/mol)
$M_{Mg(OH)_2}$	Mole mass of $Mg(OH)_2$ (g/mol)
$Q_{ex,\ in}$	Total energy of the exhaust gas at the reactor inlet in the heat storage process (kJ)
Q_{stored}	Stored energy inside the reactor in the heat storage process (kJ)
$r_{EM8block}$	Percentage of the reacted EM8block (%)
r_{mix}	The mass mixing ratio of EM8block
r_{stored}	Percentage of stored energy in the heat storage process (%)
$w_{EM8block}$	Weight of the reacted EM8block in the heat storage process (g)
w_{H_2O}	Weight of the water moving into the water tank in stage 4 of the heat storage process (g)
w_{total}	The total weight of EM8block (g)

2. Chemical heat storage system

2.1. Selection of chemical material

The chemical material adopted in this research is Magnesium hydroxide ($Mg(OH)_2$) based on its reversible reaction described by Eq. (1) Kato [13].

$$Mg(OH)_2(s) + heat \leftrightarrow MgO(s) + H_2O(g) \tag{1}$$

It was proposed that the wasted heat be stored during the dehydration of $Mg(OH)_2$ with the reaction products of MgO and H_2O, and that the stored energy be released in the hydration of MgO. The storage density of $Mg(OH)_2$ is 81 kJ/mol. However, the thermal conductivity of the pure $Mg(OH)_2$ is very low (within 0.15–0.16 W/m.K [11]). To increase the heat transfer efficiency, a new compound was proposed by Massimiliano [11]. It was the combination of $Mg(OH)_2$ and expanded graphite (EG) with the mass ratio of 8:1 and in the block state (EM8block). EM8block was adopted in the present study (Fig. 1).

As reported in [11], the advantages of this material compared with pure $Mg(OH)_2$ include:

- high thermal conductivity: The thermal conductivity of EM8block is about ten times higher that of the pure $Mg(OH)_2$ pellets (the thermal conductivity of EM8block is 1.5–1.7 W/mk compared with 0.15–0.16 W/m.K of $Mg(OH)_2$ pellets as shown in Table 1.
- great density: Compared with the density of the bed of the pure Mg $(OH)_2$ pellets were randomly arranged in the reactor, the density of EM8block is higher.
- reduced void fraction of the bed: it enhances the contact between the chemical material and the inner surface of the storage tank and consequently improves the thermal conductivity of the reactor.

The main properties of $Mg(OH)_2$ pellets and EM8block are shown in Table 1.

2.2. The principle of CHS using to cover exhaust gas energy of IC engine

To store the heat energy of the exhaust gas, it was proposed that two main devices would be installed in the exhaust gas pathway of an IC engine, a reactor and a water tank. The reactor is located between the engine exhaust port and the catalytic converter. The principle of the heat storage process is shown in Fig. 2.

In the heat storage process, heat is transferred from the exhaust gas to Magnesium hydroxide ($Mg(OH)_2$) and converts to magnesium oxide (MgO) and water vapour (H_2O) in the dehydration reaction in the reactor as shown in Eq. (2). During this process, MgO is retained inside the reactor, the water vapour moves into and condenses in the water tank in Eq. (3). As the reaction products, MgO and water vapour are stored separately in the reactor and the water tank.

$$Mg(OH)_2(s) + Q_d \rightarrow MgO(s) + H_2O(g) \tag{2}$$

$$H_2O(g) \rightarrow H_2O(1) + \Delta H_1 \tag{3}$$

Fig. 3 shows the heat output process. As shown in Fig. 3, the water liquid in the water tank is heated by a small electrical resistor and evaporates. The water vapour flows from the water tank into the reactor and reacts with the solid MgO(s) in the reactor. Heat energy releasing from the hydration reaction in the reactor, Q_h, is transferred to the object to be heated, here is the engine intake air. Heat energy is released from the hydration reaction of MgO and water vapour as follows:

$$H_2O(1) + \Delta H_2 \rightarrow H_2O(G) \tag{4}$$

$$MgO(s) + H_2O(g) \rightarrow Mg(OH)_2(s) + Q_h \tag{5}$$

2.3. Reactor design

The reactor was designed based on the experimental data of the tested engine, D1146TI diesel engine. The reactor consists of one shell and one tube. EM8block is stored inside the tube as shown in Fig. 4. The major dimensions of the reactor are listed in Table 2.

The reactor consists of one shell and one tube. EM8block is stored inside the tube, and the exhaust gas flows in the space between the shell and the tube.

In the heat storage process, the exhaust gas flows into the shell at

Fig. 1. EM8block inside the reactor.

Table 1
The main properties of $Mg(OH)_2$ pellets and EM8block [11].

Parameter	Unit	$Mg(OH)_2$ pellets	EM8block
Density of bed	g/cm^3	0.966	1.002
Working temperature	°C	250–800	250–800
Reaction enthalpy	kJ/mol	81	81
Thermal conductivity	W/m.K	0.15–0.16	1.5–1.7

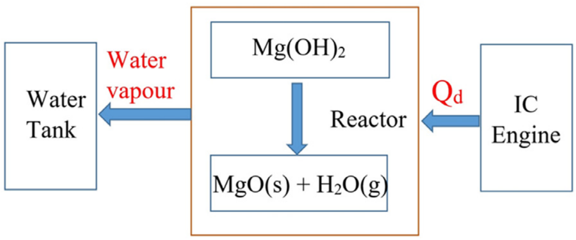

Fig. 2. The heat storage process.

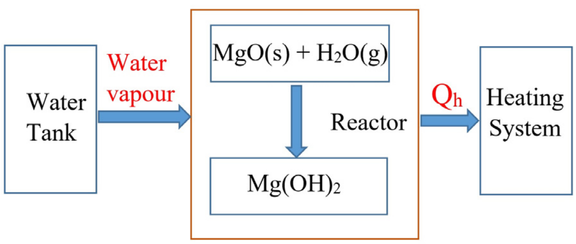

Fig. 3. The heat output process.

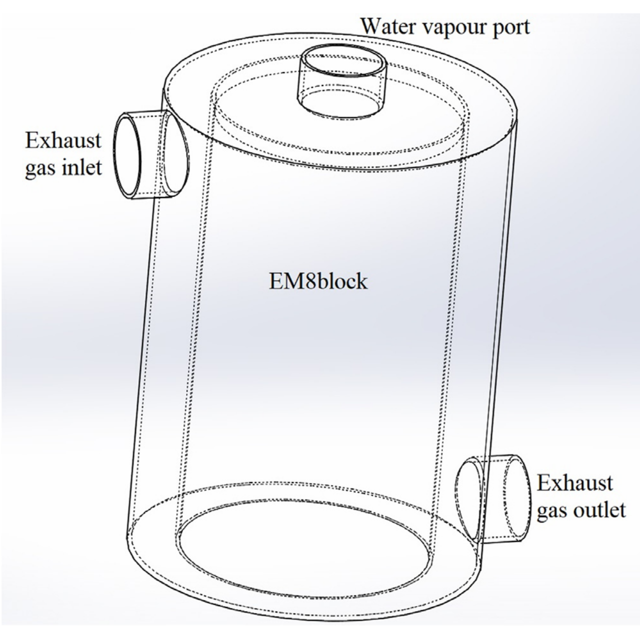

Fig. 4. The reactor design.

the exhaust gas inlet and out at the exhaust gas outlet port, while heat energy is transferred from the exhaust gas to EM8block through the wall of the reactor. The dehydration reaction of EM8block starts inside the tube of the reactor when the temperature of EM8block reaches the reaction temperature of 280 °C.

In the heat output process, the water liquid in the water tank evaporates and flows to the reactor through the water vapour port. The heat energy releasing from the hydration reaction in the reactor is then

Table 2
The reactor parameters.

Parameter	Internal diameter (mm)	Thickness (mm)	Length (mm)
Tube	260	6.5	500
Shell	360	6.5	500
Exhaust gas inlet	88.9	3.05	
Exhaust gas outlet	88.9	3.05	
Vapour port	88.9	3.05	

Table 3
Major specifications of the diesel engines.

Parameters	Unit	Value
Number of cylinders		6
Number of strokes		4
Bore	mm	111
Stroke	mm	139
Displacement volume	cc	8071
Compression ration		16.7:1
Maximum power	kW	151@2200rpm
Maximum Torque	N.m	735@1400rpm

transferred to the engine intake air.

EM8block was filled up to a height of 460 mm when the total mass is 24.46 kg.

3. Experimental apparatus and methods

Experiments were conducted on the D1146TI diesel engine in the Engine Laboratory at the Hanoi University of Science & Technology in Vietnam. D1146T1 is a 4-stroke 6-cylinder Diesel engine for trucks in Vietnam. The major specifications of the engine are shown in Table 3.

In IC engine, besides the useful work defining as the engine power, a part of the total energy is lost in the exhaust gas. The energy of the exhaust gas is determined by the sum of the energy of exhaust gas components (H_2O, CO_2, CO, O_2, NO_x, HC, etc.) at the exhaust gas temperature as follows:

$$\dot{Q}_{ex} = \dot{Q}_{H_2O} + \dot{Q}_{CO_2} + \dot{Q}_{CO} + \dot{Q}_{O_2} + \dot{Q}_{NO_x} + \dot{Q}_{HC} \quad \text{(kW)} \tag{6}$$

Where $\dot{Q}_{ex}$ is the energy of the exhaust gas (kW) and $\dot{Q}_{H_2O}$, $\dot{Q}_{CO_2}$, $\dot{Q}_{CO}$, $\dot{Q}_{O_2}$, $\dot{Q}_{NO_x}$, $\dot{Q}_{HC}$ are the energy of the exhaust gas components (H_2O, CO_2, CO, O_2, NO_x, HC) (kW).

The energy of an exhaust gas component can be written function of the mass ow rate and the enthalpy of the exhaust gas component as follows:

$$\dot{m}_{com} h_{com} \quad \text{(kW)} \tag{7}$$

Where $\dot{Q}_{com}$ is the energy of the exhaust gas component (H_2O, CO_2, CO, O_2, NO_x, HC) (kW), h_{com} is the enthalpy of the exhaust gas component (kJ/kg) at the exhaust gas temperature and $\dot{m}_{com}$ is the mass flow rate of the exhaust gas component (kg/s). The mass flow rate of a component can be calculated with Eq. (8).

$$\dot{m}_{com} = r_{com}.\ \dot{m}_{ex} \quad \text{(kg/s)} \tag{8}$$

Where r_{com} is the mass percentage of the component in the exhaust gas (%) and $\dot{m}_{ex}$ is the mass flow rate of the exhaust gas (kg/s). The mass flow rate of the exhaust gas is defined as the sum of the mass flow rate of the fuel, $\dot{m}_{fuel}$ (kg/s), and the air, $\dot{m}_{air}$ (kg/s), at the inlet of IC engine as follows:

$$\dot{m}_{ex} = \dot{m}_{fuel} + \dot{m}_{ex} \quad \text{(kg/s)} \tag{9}$$

Besides the engine power and the energy lost in the exhaust gas, the other energy losses of IC engine, $\dot{Q}_{other}$ (kW), including energy losses in the combustion, transmission, noise, cooling systems, etc. is determined as follows:

$$\dot{Q}_{other} = \dot{Q}_{total} - P - \dot{Q}_{ex} \quad (kW) \tag{10}$$

Where $\dot{Q}_{total}$, is the amount of fuel chemical energy releasing in the combustion process and P is the engine power (kW).

$$\dot{Q}_{total} = \dot{m}_{fuel}.\ Q_{HV} \quad (kW) \tag{11}$$

Where Q_{HV} is the heating value of the fuel (kJ/kg). Fig. 5 shows the experimental result of energy distribution varied with the engine load of the tested Diesel engine. As shown in Fig. 5, the energy lost by the exhaust gas could be up to 70%. The research aim is to store and reuse as much as possible the wasted exhaust gas energy.

Fig. 6 shows a photo of the experiment apparatus set up in the AVL engine test-bed and the schematic diagram of the test rig was shown in Fig. 7.

Three thermostats were placed to measure the exhaust gas temperatures at the inlet and outlet of the reactor (T_1, T_2), EM8block temperature (T_3) in the heat storage process and the engine intake air temperatures at the reactor inlet and outlet (T_4, T_5), the wall temperature of the tube of the reactor (T_6) in the heat output process. The pressure difference between the inlet and outlet of the reactor was measured by a manometer. The weight of water vapour moving into or from the water tank was measured by an electrical balance. The velocity of the heated air was determined by an air velocity meter. All experimental data including T_1, T_2, T_3, T_4, T_5, T_6, pressure difference, the weight of water in the water tank, the air velocity and operation data of the engine were recorded by a data acquisition system.

In the heat storage process, the experiments were conducted at 60%, 70% and 80% of engine load. At an engine load, the experiments were conducted for about 60 min with the data recorded every 2 min. Each experiment was performed in four stages.

- Stage 1 (The heating stage): the temperature of EM8block (T_3) increased from the ambient temperature to around 80–90 °C.
- Stage 2 (The heating and evaporating stage): the moisture inside EM8block evaporated and moved to the water tank until T_3 was around 110–120 °C (the moisture from the uncompleted drying process of EM8block and the environment)
- Stage 3 (The heating stage): EM8block was heated to the reaction temperature of $Mg(OH)_2$ (T_3 was around 250–280 °C).
- Stage 4 (The heating and storing stage): The CHS system was heated continuously and the dehydration reaction of EM8block occurred in the reactor. The wasted energy was stored by the dehydration reaction of $Mg(OH)_2$. The water vapour releasing from the dehydration reaction of EM8block flowed to and condensed in the water tank.

In the heat output process, the data was recorded when T_6 was in an arrange of 45 °C to 86.4 °C. Each experiment was performed in two stages.

- Stage 1 (heating the reactor): The temperature of the reactor increases due to the hydration reaction.
- Stage 2 (heating the intake air): The intake air moved into the reactor and absorbed heat energy from the reactor.

4. Results and discussions

The criteria for evaluating the CHS performance will be defined in Section 4.1. In Sections 4.2 and 4.3, results will be presented and analysed against the criteria to evaluate the performance of the CHS in the heat storage and intake air heating processes.

4.1. Criteria for evaluating the performance of CHS

In the heat storage process, the performance of the CHS system is assessed by the percentage of the stored exhaust gas heat energy and the percentage of reacted EM8block in a period of time (60 min in this study).

The weight of the condensed water, w_{H_2O}, in the water tank will be used to find the stored energy, Q_{stored} (kJ), with Eq. (12).

$$Q_{stored} = 81\frac{w_{H_2O}}{M_{H_2O}}\ (kJ) \tag{12}$$

Where M_{H_2O} is the mole mass of the water (g/mol) and 81 kJ/mol is the reaction enthalpy of $Mg(OH)_2$. The percentage of the stored energy, r_{stored} (%), in the reactor is presented as follow:

$$r_{stored} = 100\frac{Q_{stored}}{Q_{ex,in}}\ (\%) \tag{13}$$

Where $Q_{ex,\ in}$ is the total energy of the exhaust gas at the reactor inlet (kJ).

The amount of the reacted EM8block is calculated from the weight of the condensed water in the water tank with Eq. (14).

$$w_{EM8block} = \frac{1}{r_{mix}}M_{Mg(OH)_2}\frac{w_{H_2O}}{M_{H_2O}} \quad (g) \tag{14}$$

Where $M_{Mg(OH)_2}$ is the mole mass of $Mg(OH)_2$ (g/mol), r_{mix} is the mass mixing ratio of EM8block (8:9). The percentage of the reacted EM8block is calculated with Eq. (15).

$$r_{EM8block} = \frac{w_{EM8block}}{w_{total}} \quad (\%) \tag{15}$$

Where w_{total} is the total weight of EM8block (g)

In the heat output process, the stored energy was used to heat the intake air. Therefore, the temperature increase of the intake air after passing the reactor is the main factor to evaluate the performance of the CHS system. The energy storing time is also one of the criteria to evaluate the performance of a CHS. It will be compared with other systems to evaluate the CHS in the present study.

4.2. Performance of CHS in the heat storage process

As discussed in Section 3, in stages 2 and 4, water vapour from the evaporating process of the moisture inside EM8block (stage 2) and dehydration reaction (stage 4) flowed into and condensed in the water tank. Fig. 8 shows the temporal variation of EM8block temperature (T_3) and the weight of water in the water tank with time in the heat storage process at 60%, 70% and 80% engine loads. The solid lines in Fig. 8 show the temporal variation of the EM8block temperature (T_3) and dotted lines show the weight of the condensed water accumulated in the water tank

As shown in Fig. 8, the time for stage 1 as defined in Section 3 is 0–4 min for 80% engine load, 0–5 min for 70% and 0–6 min for 60% engine load. In stage 1, the water weight in the water tank did not change and the time taken depended on the engine start-up condition.

Stages 2 started when the EM8block temperature, T_3, reached 80–90 °C. The moisture inside the EM8block was evaporating and flowing into the water tank. It made the water weight in the water tank

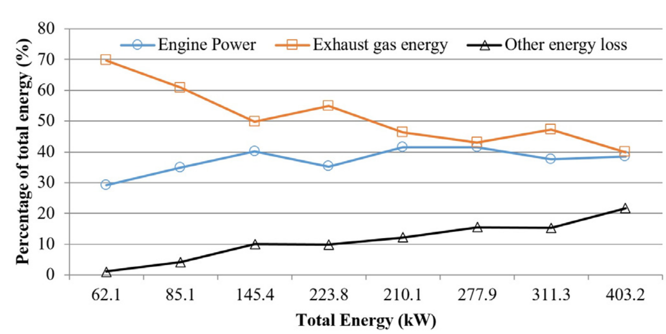

Fig. 5. The energy consumption of the engine [14].

Fig. 6. The experimental apparatus.

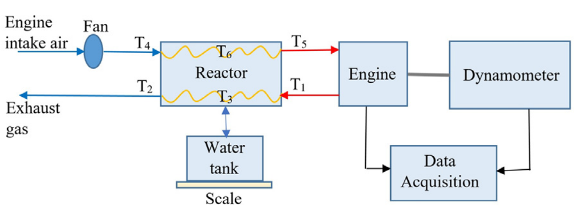

Fig. 7. Schematic diagram of the experiment apparatus.

increased. As shown in Fig. 8, stage 2 took 6, 7 and 9 min for 80%, 70% and 60% engine loads, respectively. The time for stage 2 depended on the amount of moisture inside EM8block and the engine load. It increased with the decrease of engine load.

In stage 3, EM8block was heated by the exhaust gas continuously to the reaction temperature, T_3 in a range of 250 °C to 280 °C. The time taken was approximately 18 min (from the 10th minute to the 28th minute) at 80% engine load, 22 min (from 12th minute to 34th minute) at 70% engine load and 30 min (from 15th minute to 45th minute) at 60% engine load.

In stage 4, the weight of the water in the water tank increased quickly because the water vapour generating from the dehydration reaction of $Mg(OH)_2$ flowed into and condensed in the water tank. Based on the weight of water in the water tank, the percentage of stored exhaust gas energy and the percentage of reacted EM8block were determined by Equations in 4.1 and shown in Fig. 9.

As shown in Fig. 9, at 80% engine load and 60 min after the engine starts, 61.4% of EM8block reacted to store 5.05% of the exhaust gas energy. By taking the same time of 60 min, 53.54% of EM8block reacted and 5.03% of the exhaust gas energy was stored at 70% engine load, and 33.68% of EM8block reacted to store 3.69% of the exhaust gas energy at 60% engine load. At the low load of the IC engine, the temperature of the exhaust gas was lower, so it needs more time for heating in stages 1, 2 and 3. Therefore, the time left for stage 4 decreased in the total time of 60 min in the experiment. As a consequence, the percentage of the reacted EM8block and stored energy decreased.

After the heat storage process, in the storing time, the water was stored in the water tank and the solid product of the dehydration reaction of EM8block was retained in the reactor at the ambient condition.

4.3. Application of CHS to heating intake air

The stored energy in the CHS was used to heat the engine intake air in the second part of the experiments. Because the laboratory was not air conditioned, the experiments were only conducted at the ambient temperature of 23 °C. In the air heating process, the water inside the water tank evaporated, flowed into and reacted with the solid product inside the reactor. The temperature of the EM8block after the hydration reaction in the reactor was 162 °C (the reaction temperature). The heat energy was then transferred from the high-temperature regions (reaction regions) to the low-temperature regions (unreacted regions) in EM8block and the reactor wall by heat conduction.

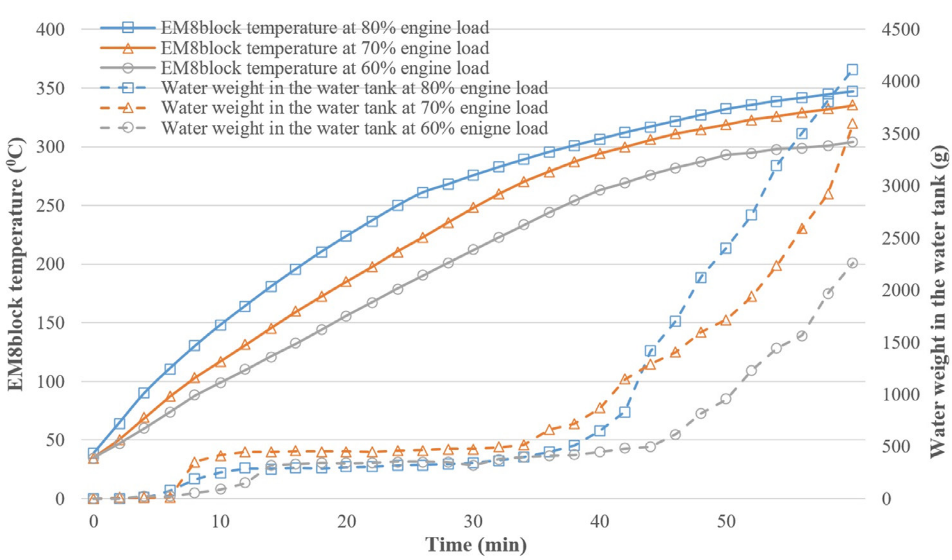

Fig. 8. The EM8block temperature and the water weight in the water at 80%, 70% and 60% engine loads.

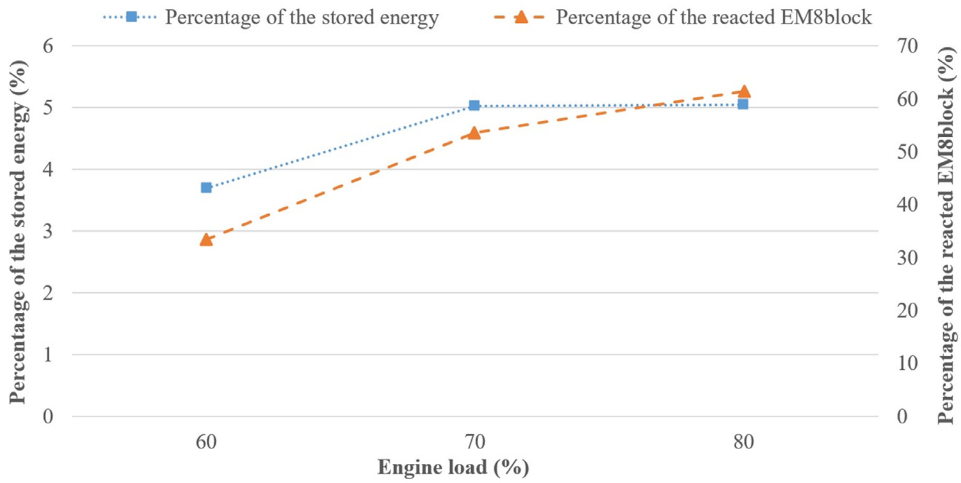

Fig. 9. Percentages of the stored energy and reacted EM8block at various engine loads.

When the temperature of the reactor wall was lower than 45 °C, the heating effect of the reactor was insignificant as shown by the small difference between T_4 and T_5 (less than 5 °C). Therefore, in the experiment, the intake air was not flowing in the reactor until the wall temperature reached 45 °C. It took 11 min for the reactor wall temperature increased from 23 °C to 45 °C.

The temperature of the reactor wall (T_6) depended on the reaction inside EM8block, and the reaction carried on with the supplied water moving from the water tank into the reactor. As shown in Fig. 10, the temperature of the reactor wall increases linearly with the increase of the mass of water vapour in the reaction. In the linear regression equation, the independent variable x is the mass of the water and the dependant variable y is the temperature of the reactor wall. The correlation coefficient, R, of 0.9785 shows a good agreement between the experimental data and the data calculated with the linear equation, except in the condition when the reactor wall temperature is lower than 48 °C. This linear function between the mass of the water vapour and the temperature of the reactor wall can be useful for predicting and controlling the reactor wall temperature and consequently, the heated air temperature.

Fig. 11 shows the variation of the intake air temperature with the temperature of the reactor wall. In the linear regression equation, x is the reactor wall temperature and y is the temperature of the heated air at the reactor outlet. The correlation coefficient, R, is 0.9966. This linear function can be useful for predicting the heated air temperature based on the reactor wall temperature. At the ambient temperature 23 °C, the heated air temperature after going through the reactor increased by 5.7 to 17.3 °C depended on the temperature of the reactor wall.

Given the temperature of the heated air, the required temperature of the reactor wall (T_6) can be calculated with the linear regression equation in Fig. 11. To get T_6 as required, the required mass of water required for the reaction can then be determined based on the linear regression equation shown in Fig. 10.

Compare with other TES systems applying to cover exhaust gas energy of IC engine, the main advantages of the CHS system are the high storage energy and the long storing time as shown in Table 4. However, the drawback of this system is that it required the start-up time in the air heating process.

The heated air, after going through the CHS system, could be used for heating the engine, lubricant in IC engines or batteries, cabin in the hybrid vehicle. Cold engine starting has been one of the issues to be addressed in engine research for many years. In the cold weather, it is difficult for the fuel in atomization, evaporation and the mixture with the air to create the correct air/fuel ratio for complete combustion. The incomplete combustion leads to the increase in the fuel consumption and pollutant emissions in the cold start process. Therefore, heating the engine in the cold weather is necessary to reduce the fuel consumption of the engine. CHS may provide the stored heat for engine to start in cold weather. Compare with the TES systems in [16], the total volume

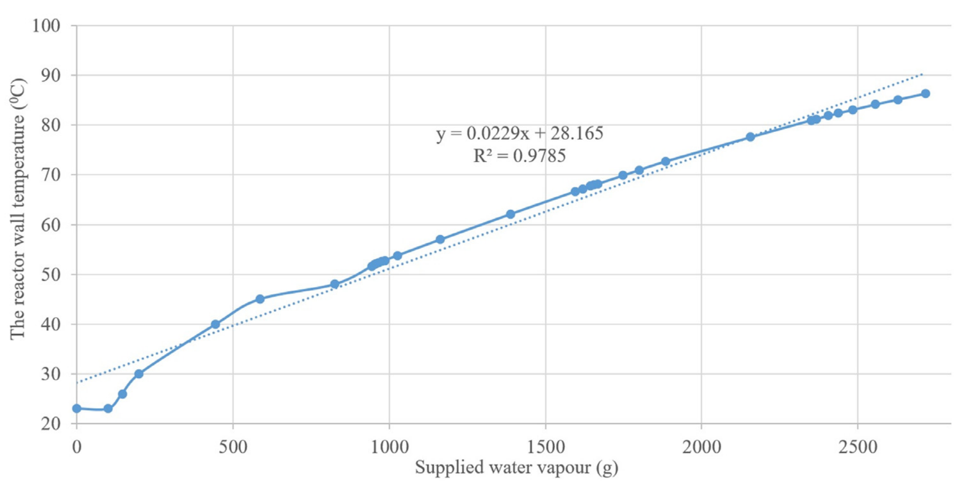

Fig. 10. Variation of temperature of the reactor wall with the mass of the supplied water vapour.

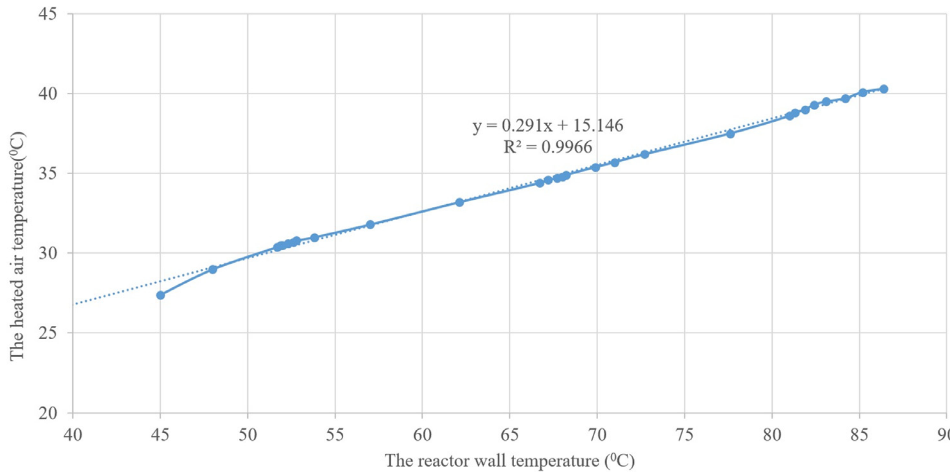

Fig. 11. Variation of the heated air temperature with the temperature of the reactor wall.

of the CHS system in the current study is 3.3 times higher than that of the TES system, however, the stored energy of the CHS is 13 times higher. Moreover, the storing time of the CHS system is longer when the stored energy of the TES system in [16] was only available in 12 h.

Moreover, the low temperature of the lube oil in the cold start process and in the cold weather makes the viscosity of the lube oil increases. The high viscosity of the lube oil leads to the high friction losses of the engine and it affects to the engine efficiency. Therefore, heating the lube oil in the cold start process and the cold weather is necessary. From the experimental results, it could be seen that the high temperature of the heated air after going through CHS is possible to increase the lube oil. Compared with the TES system in [15]. The size of the CHS system in the current study is smaller, however, the stored energy is higher. Besides, the storing time of the CHS system in the current study is longer than the TES system in [15] and Tessa TES system in [17] as shown in Table 4.

For hybrid vehicles, it is well known that a battery's efficiency is maximized at a certain temperature. The suitable temperature for the batteries should be 25 °C to 45 °C [18] and heating them in the cold weather is a requirement to maintain the lifespan. Moreover, with hybrid vehicles, when the electric motor is in being used, it does not make much heat energy in operation as IC engine. Therefore, the energy required for heating the cabin in the cold weather increases. In this case, the high temperature of the heated air after going through the CHS system could be used to heat the cabin or the batteries of hybrid vehicles to the best temperature range.

5. Conclusions

A CHS system using $Mg(OH)_2$ has been developed to store the exhaust gas heat energy of a Diesel engine. The prototype of the CHS reactor was designed and built. Experiments were conducted on a Diesel engine (D1146TI) equipped with the CHS to investigate the performance of this CHS system and its application to heating the intake air.

In the heat storage process, the percentage of the stored heat energy decreased with the decrease of the engine load. At 80% engine load, 5.05% of the exhaust gas energy was stored and 61.41% of EM8block reacted within 60 min. The percentage of the stored exhaust gas energy, the reacted EM8block decreased to be 3.69% and 33.68% when the engine load reduced to 60%.

In the heat output process, one application has been investigated using the stored heat energy to heat engine intake air, aiming to contribute to the solutions for engine cold start. At the ambient temperature 23 °C, the temperature of the heated air could be increased from 5.7 to 17.3 °C. The higher temperature of the heated air after going through the CHS system could be used to heat the engine, lubricant in IC engine vehicles or the battery, cabin in hybrid vehicles.

Compared with other thermal storage systems, the CHS investigated in the present study has higher stored energy and longer storing time. However, the start-up time in the heat output process is a drawback of this system.

Author statement

Duc Luong Cao: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. **Guang Hong:** Conceptualization, Methodology, Resources, Validation, Writing - Review & Editing, Supervision. **Tuan Anh Le:** Validation, Resources, Supervision

Table 4
The main parameters of the CHS and other TES systems.

Parameter	Pandiyarajan's TES system [15]	M.Gumus's TES system [16]	Tessa TES system [17]	CHS system in the current study
Application	Heating the lube oil	Heating the engine	Heating the engine, the cabin	Heating the intake air
Size	A heat exchanger: 450 ID x 720 H mm A TES tank: 323 ID x 500 H mm	A storage tanks: 610 W x 710 D x 230 H mm	A storage tank: 220 OD x 400 L mm	A reactor: 360 OD x 500 H mm A water tank: 20 OD x 30 H mm
Stored energy	19.500 kJ	2277 kJ		30.197 kJ
The working temperature	120°C	32.4°C	230°C	90°C
Storing time	90 h	12 h	12 h	More than 90 h
Start-up time	Short	Short		Long

ID: inside diameter, OD: outside diameter, H: height, W: Width, D: depth, L: length.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.est.2020.101311.

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