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Investigation of chemical heat storage processes for recovering exhaust gas energy in internal combustion engines

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Abstract

Improving the energy efficiency of the IC engine and hybrid vehicles has become more and more important. Chemical heat storage system is one of the approaches to address it by utilising the wasted energy. This study was aimed to develop a chemical heat storage (CHS) system using magnesium hydroxide ($Mg(OH)_2$) to recover the thermal energy wasted by the exhaust gas in internal combustion (IC) engines. The stored heat can be used to heat the intake air, catalysts, lubricants in IC engines and batteries in hybrid vehicles. Experiments were conducted on a diesel engine (D1146TI) to estimate the efficiency of CHS technology in the heat storage process. Experimental results showed that at engine load 60% to 80%, 33.68% to 61% of the chemical material reacted with 3.69% to 5.05 % heat energy of exhaust gas stored in one hour time. The percentages of the reacted chemical material and the stored exhaust gas heat energy decreased with the decreased engine load.

Introduction

CHS system

CHS is one kind of thermal energy storage system. It is used to transfer heat to stored energy in the heat storage process and release in the heat output process. It is based on the reversible reaction of a chemical material as follow

A + heat ↔ B + C

Heat energy is absorbed in the heat storage process by a chemical A to become two components B and C. In the heat output process, two products B and C are mixed together to become the initial chemical A and heat is released. Compare to other thermal energy storage systems, CHS has a higher energy density (ten times higher than sensible heat storage system or five times higher than latent heat storage) and the energy can be stored for a longer time with a mall heat loss (B, C are stored separately and in the ambient temperature).

CHS system has been applied to saving the energy for the domestic or industrial area. In the domestic, the system has been used to store solar energy for the hot water system. Solar energy is a very important source of renewable energy but it is intermittent and only available a few hours per day. Therefore, CHS system could be connected with the solar energy capturing system to utilise the efficiency of the whole system [1]. The stored energy can be used in the night time or in the winter.

In the industrial area, CHS has been used in the power plants to store heat energy in the off peak hours and release in the on peak electricity times [2], [3]. CHS technology would make easier to manage the load variations of the power plant and contribution to the operation of a smart grid.

In the IC engine, the exhaust gas is a significant source of the energy loss (approximately 22% of total energy) [4]. If a part of this heat loss could be used for other purposes, the efficiency of the cycle can be increased and fuel consumption can be reduced. By this reason, IC engine can become a potential object of CHS system. The stored energy after that could be used to heat the engine, catalyst, lubricant in IC engine vehicles or the battery, the cabin in hybrid vehicles.

Applying CHS to cover exhaust gas energy of IC engine.

The chemical material (CM) adopted in this research is the compound of $Mg(OH)_2$ and expanded graphite in the mass mixing ration is 8:1 and in the block state (EM8block) [3]. The reaction temperature of EM8block is suitable with the exhaust gas temperature. Besides, it has the high density and thermal conductivity compared to the raw $Mg(OH)_2$. In addition, in the block state, using this material can reduce the void fraction of the bed. It will enhance the heat transfer process inside the chemical material. The main properties of the material are shown in table 1

Parameters	Unit	Value
Mass mixing ratio (r_{mix})		8:9
Density of bed	g/cm^3	1.002
Working temperature	K	550-800

Table 1: The main properties of EM8 block [3].

CHS system using EM8block to recover exhaust gas energy of IC engine is based on the reversible reaction of $Mg(OH)_2$ as follow

$$Mg(OH)_2(s) \leftrightarrow MgO(s) + H_2O(g)$$

The principle of this system is shown in figure 1

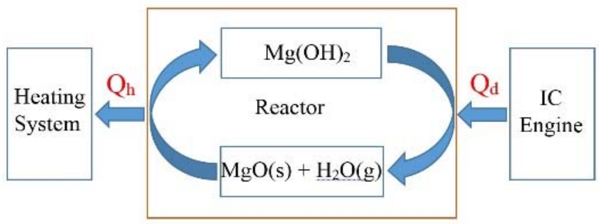

Figure 1: The principle of CHS system using EM8block to store exhaust gas energy of IC engine

In the heat storage process, magnesium hydroxide ($Mg(OH)_2$) absorbs the waste heat of the exhaust gas (Q_d) and converts to magnesium oxide (MgO) and water vapor in the dehydration reaction in the reactor chamber. Magnesium oxide after that is stored inside the reactor. Water vapour moves into a water tank and condenses to water liquid.

In the heat output process, the water liquid in the water tank is heated by a small electrical resistor and evaporates. The water vapor after that flows from the water tank into the reactor chamber. In the reactor chamber, heat energy (Q_h) from the hydration reaction of MgO and water vapour is absorbed by the engine intake air before coming to the heating system.

Tested engine

The IC engine using in this research is D1146TI diesel engine (the engine equipped on buses in Vietnam) at Hanoi University of Science & Technology. The main parameters of the engine are shown in table 2

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

Table 2: The major specifications of tested engines.

The engine consumption of the engine is shown in figure 2

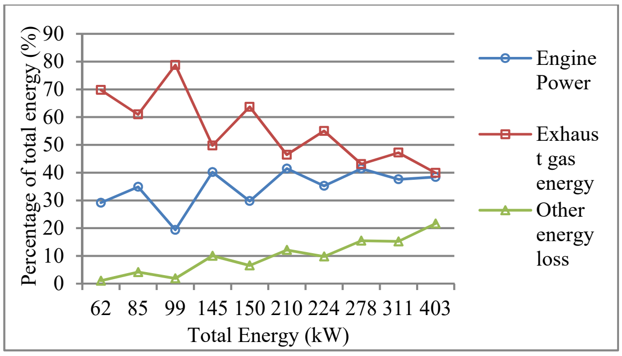

Figure 2: The energy consumption of the diesel engine [5].

The total energy is found from the fuel consumption of the engine. The engine power is calculated based on the engine speed and torque. From the exhaust gas temperature and its components (were acquired by the AVL test-bed), the exhaust gas energy gases are the sum of the energy of exhaust gas's components.

As shown in figure 2, in the diesel engine, the wasted energy in the exhaust gas is significant. In some conditions, this energy loss can increase to 70%. Therefore, the efficiency of the engine would be enhanced if a part of wasted heat energy can be reused.

Experimental results of the heat storage process in the diesel engine

Experimental apparatus and procedure

The experiment instruments including a dynamometer, a D1146TI diesel engine, a fuel balance, a reactor, a water tank, a scale and other instruments using to analyse the exhaust gas and measure temperatures, pressure change were set up in the AVL engine test-bed. The experiment apparatus and the schematic diagram in the heat storage process are shown in figure 3 and 4.

In the heat storage process, the reactor is located between the engine exhaust port and the catalytic converter. Water vapour from the dehydration reaction of $Mg(OH)_2$ in the reactor chamber moves into the water tank. Therefore, the weight of the tank increases and it is measured by an electronic balance. All data is collected by a data acquisition.

Figure 3: The experimental apparatus

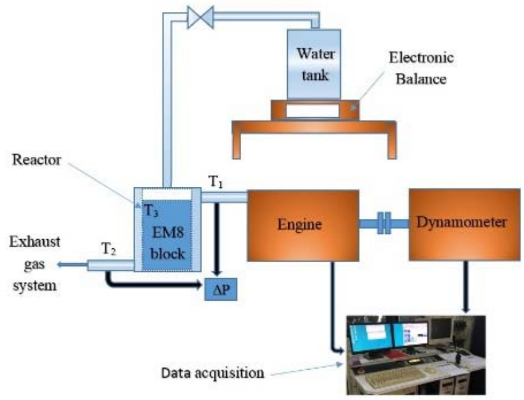

Figure 4: Schematic diagram of the experiment apparatus of the heat storage process

Because of the moisture content in the chemical material (from uncompleted drying process on the material built process and the environment), the experimental process occurs in four stages as follows:

- Stage 1: The temperature of EM8block (T_3) increases from the ambient temperature to around 80^0C. In this stage, the exhaust gas energy is used to heat the reactor and CM.
- Stage 2: When T_3 reaches around 80^0C, the moisture inside CM evaporates and moves to the water tank. The weight of the water in the water tank increases until T_3 is around 110^0C. At this temperature, all moisture inside CM is evaporated and condensed in the water tank. In this stage, the waste heat is used not only for heating the reactor and CM but also for evaporating the moisture inside CM. The duration of this stage depends on the amount of moisture inside CM.
- Stage 3: After all moisture inside the material is evaporated and condensed in the water tank, the weight of the water tank is constant. In stage 3, the reactor and CM receive heat energy from the exhaust gas and T_3 increases to around 250^0C – 280^0C.

- Stage 4: The dehydration reaction of $Mg(OH)_2$ takes place. The water vapor from the dehydration reaction of $Mg(OH)_2$ moves out of the reactor and condenses in the water tank. The weight of the water in the water tank increases very quickly. In this stage, almost heat energy is used for the chemical reaction inside the reactor.

Experimental results of the heat storage process in the diesel engine

The experiments were conducted in the diesel engine at engine loads (60%, 70% and 80%) in 60 minutes and the data was recorded every 2 minutes. From the experimental data, the energy of the exhaust gas at the inlet and outlet were determined. The captured energy of the reactor was the energy difference of the exhaust gas between inlet and outlet of the reactor. The results were calculated every 2 minutes (a calculation step) using the average value of the temperature and exhaust gas components. The captured energy of the reactor at 80% engine load is shown in figure 5.

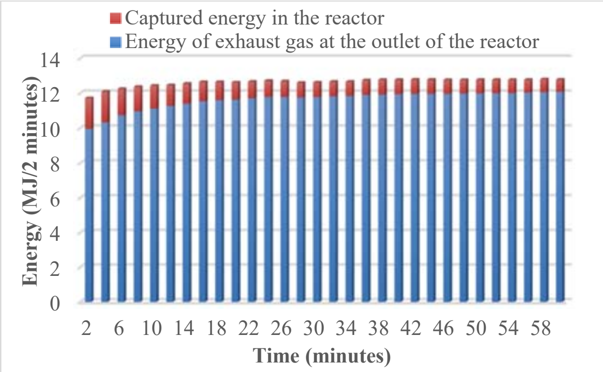

Figure 5: Energy of the exhaust gas at 80% engine load

In the heat storage process, the captured energy as shown in figure 6 is used for purposes:

- Heating the reactor
- Heating the chemical material
- Other heat losses and storage: including energy for evaporating the moisture inside the CM (stage 2), energy storage in CM (stage 4), other heat losses (connecting pipers, reactor to the environment, etc).

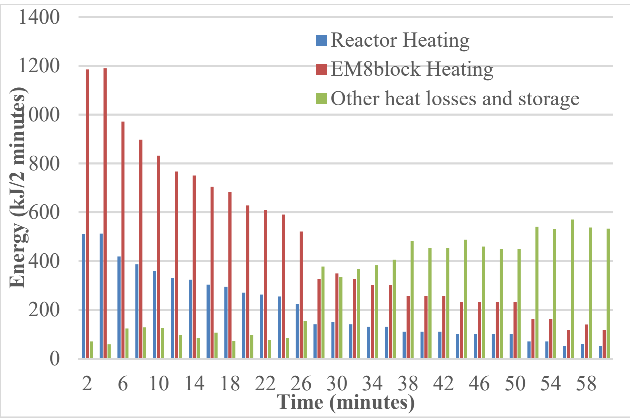

Figure 6: The distribution of the captured energy in the reactor at 80% engine load

Assume the temperature of CM and the reactor are uniform in a calculating step, the heat energy using to heat them can be calculated using the following equations:

$$Q_r = m_r.C_r(T_{r,n+1} - T_{r,n}) \quad (1)$$

$$Q_{CM} = m_{CM}.C_{CM}(T_{CM,n+1} - T_{CM,n}) \quad (2)$$

Where

Q_r, Q_{CM}: Heat energy using for heating the reactor and CM (kJ)

m_r, m_{CM}: The mass of the reactor and CM (kg)

C_r, C_{CM}: Specific heat of the reactor and CM (kJ/kg.K)

$T_{r,n+1}$, $T_{CM,n+1}$: The temperature of the reactor and CM at step n+1

$T_{r,n}$, $T_{CM,n}$: The temperature of the reactor and CM at step n

As shown in figure 6, at 80% engine load, the time for stage 1 as defined above is from 0-6 minutes. After that, from the 6th minute to 10th minute, the "other heat losses and storage" section is higher because a part of the exhaust gas energy is used for evaporating the moisture inside CM (stage 2). After 10 minutes, in stage 3, the captured energy is only used for heating the reactor and CM and "other heat losses and storage" section is back to normal. From the 26th minute, the "other heat loss and storage" section increases sharply because in this stage (stage 4), heat energy starts being stored in CM. In this stage, almost energy is stored and the captured heat used for heating the reactor and the chemical material are small.

Besides the "other heat losses and storage" section, four stages of the heat storage process can be expressed by the weight difference of the water tank (the weight of the water from the chemical reaction moves into the water tank). The results at 80% and others engine loads (60% and 70%) could be seen in figure 7.

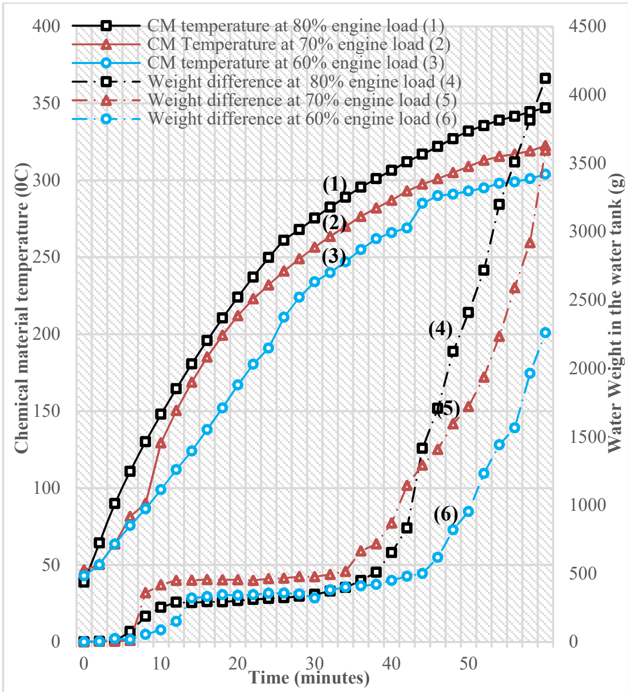

Figure 7: CM temperature (T_3) and the water weight in the water tank in the heat storage process at 80%, 70% and 60% engine loads

At 80% engine load, the water weight in the water tank does not change in stage 1 from the first minute to 6th minute. It slightly increases from the 6th minute to 10th minute in stage 2 when the moisture inside the CM evaporates and condenses in the water tank. Its return to the unchanged stage in stage 3 from 10th minute to 26th minute. In the last stage (stage 4), it sharply increases when the dehydration reaction of $Mg(OH)_2$ occurs and the water vapour condenses in the water tank. Other results for other engine loads (60%, 70%) are also shown in figure 7.

It can be seen that, at the lower engine loads, the heating time (three first stage) is longer. This comes from the lower temperature of the exhaust gas. The heating time increases from 26 minutes at 80% engine load to approximately 40 minutes at a lower load (60%). The longer heating time means the start-up time of the reactor is higher.

Based on the reaction enthalpy of $Mg(OH)_2$ (81 kJ/mol) [3], the stored energy can be found using equation 3.

$$Q_{store} = 81\frac{m_{H_2O}}{M_{H_2O}}\ (kJ) \quad (3)$$

Where

Q_{store}: The stored energy in the reactor.

m_{H_2O}: The weight of water

M_{H_2O}: The mole mass of the water

From stored energy and total energy of the exhaust gas, the percentage of the exhaust gas energy is stored inside the reactor can be found.

Besides, the amount of the reacted EM8block in the heat storage process will be calculated using equation 4

$$m_{EM8block} = 1.125 M_{Mg(OH)_2}\frac{m_{H_2O}}{M_{H_2O}} \quad (4)$$

Where

$m_{EM8block}$: The amount of reacted EM8block within 60 minutes

$M_{Mg(OH)_2}$: The mole mass of $Mg(OH)_2$

Parameters	Unit	80%	70%	60%
Weight of water inside the storage tank	Kg	4.12	3.59	2.26
Weight of reacted $Mg(OH)_2$	Kg	13.35	11.64	7.32
Weight of reacted EM8block	Kg	15.02	13.1	8.24
Stored energy within 60 minutes	MJ	18.54	16.168	10.17
Total energy of exhaust gas	MJ	366.94	321.075	275.2
Percentage of stored exhaust gas energy	%	5.05	5.03	3.69
Percentage of reacted chemical material	%	61.4	53.54	33.68

Table 3: Energy storage within 60 minutes

Table 3 shows experimental results at 80%, 70% and 60% engine loads of the diesel engine. At 80% engine load, it took 60 minutes for 5.05% of the exhaust gas energy is stored by 61.4% of CM in the reactor. By taking the same time of 60 minutes, 53.54% of CM was reacted and 5.03% of the exhaust gas energy was stored at 70% engine load. At 60% engine load, these numbers were 33.68% of reacted CM and 3.69% of the exhaust gas energy was stored.

It can be seen that, at the high engine load (80%), 61.4% possible storage heat was stored in 60 minutes but this number decreased sharply to 33.68% at lower load (60%). Along with that, the efficiency of the reactor decreased from 5.05% to 3.69%. The main reason is the low temperature of exhaust gas at the low engine loads. At the low loads of the IC engine, the time taken for the heating process (three first stages) increased so the time for dehydration reaction process was decreased in 60 minutes of the operation. Besides, at the lower engine load, it needs more time for heating the inner layers of the material to reach to the reaction temperature.

Conclusions

A CHS system has been developed to test the operation of the system in the diesel engine. In this system, heat energy of the exhaust gas used for heating the reactor, CM, evaporating the moisture and storing in CM. The experimental results showed that, at 80% engine load, 5.05% of the exhaust gas energy was stored in 60 minutes with 61% reacted CM. The percentages of the reacted CM and efficiency of the reactor reduce with the reduced load of the engine.

The heating time (three first stages) is a very important factor affecting the operation of the CHS. It increases with the decreased of the engine load. The main reason is the low exhaust gas temperature at the low loads of the engine. It can be improved at the higher engine loads or in the gasoline engine when the exhaust gas temperature is higher.

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