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Preliminary comparison of chemical heat storage systems for saving exhaust gas energy in gasoline and diesel engines

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Abstract

Thermal energy storage has become more important to utilizing the wasted energy and improving the overall efficiency of energy systems. This study was aimed to develop a chemical heat storage system using magnesium hydroxide ($Mg(OH)_2$) and its dehydration and hydration reactions to recover the thermal energy wasted by the exhaust gas in internal combustion (IC) engines. Experiments and simulations were conducted on a gasoline engine (Toyota Aurion 2GR-FE 3.5L) and a diesel engine (D1146TI) to compare the efficiency of chemical heat storage (CHS) technology in two difference kinds of IC engines. With the same CHS system and working time, the amount of energy stored by the reactor in the heat storage process in the gasoline engine is higher than that in a diesel engine because the average temperature of the exhaust gas in the gasoline engine is higher than that in the diesel engine. Alternatively the time for storing the same amount of heat energy in the gasoline engine will be shorter than that in the diesel engine.

1 Introduction

In today's modern life, IC engines are still widely used in many fields, such as transportation, construction or agricultural sectors. However, a significant amount of fuel energy is lost as wasted heat through exhaust gas and cooling systems in IC engine. If the heat loss in the exhaust gas can be stored and used, the overall efficiency of an IC engine will be increased. When a certain amount of exhaust gas heat could be recovered, the fuel could be saved and the environment pollution could be reduced.

This research is focused on applying CHS to store energy wasted by the exhaust gas in IC engines. The chemical material adopted in the CHS device in this research is Magnesium hydroxide ($Mg(OH)_2$) based on its reversible reaction as follow:

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

In the heat storage process, Magnesium hydroxide absorbs the wasted heat of the exhaust gas and converts to magnesium oxide and water vapor in the dehydration reaction in the reaction chamber. MgO is retained inside the reactor chamber, and the water vapor produced from the chemical reaction is moved into a condenser and condensates to the liquid state.

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In the heat output process, the water vapor flows into the reactor chamber. The reaction takes place between the MgO and the water vapor to become $Mg(OH)_2$ and heat energy is released in this reaction.

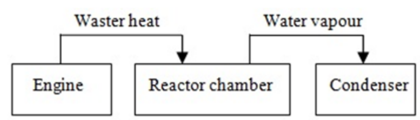

Figure 1: The heat storage process [1]

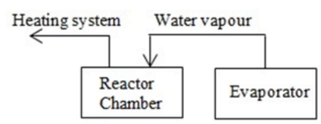

Figure 2: The heat output process [1]

The thermal conductivity of the packed bed of $Mg(OH)_2$ pellets is too low within 0.15 – 0.16 W/m.K [2], which affects the heat absorption capacity of chemical material and thereby decreases the efficiency of the reactor. To increase the heat transfer efficiency of the chemical material, a new $Mg(OH)_2$ compound suggested by Massimiliano was the combination of $Mg(OH)_2$ and expanded graphite (EG) with the mass mixing ratio 8:1 and in the block state (EM8 block). As reported in [2], the advantages of EM8, compared with pure $Mg(OH)_2$, include:

- Higher thermal conductivity: The thermal conductivity of EM8 block is about ten times that of the pure $Mg(OH)_2$ pellets.
- Higher density: The density of EM8 block is 1.6 times that of $Mg(OH)_2$ pellets.
- Reduced void fraction of the bed: it will enhance the contact between the packed material and the inner surface and consequently improve the thermal conductivity of the reactor

Parameters	Unit	Value
Mass mixing ratio (r_{mix})		8:9
Density of bed	g/cm^3	1.002
Working temperature	K	297-800
Reaction enthalpy	kJ/mol	81
Thermal conductivity	W/m.K	1.5 – 1.7
Heat storage capacity in 1 hour	MJ/m^3	700

Table 1: The main properties of EM8 block [2].

2 Potential applications of CHS technology to IC engines

2.1 Applications of CHS to vehicle engines

In IC engine vehicles, the cold start process is the major source for pollutant emissions, including uncombusted hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Besides, The fuel consumption of the vehicle engine is therefore increased during the cold start. Kunze [3] presented results that showed the difference in the fuel consumption between a cold start and a warm start of a gasoline engine. When the temperature increased from 25^0C to 90^0C, the fuel consumption decreased by 10% in the engine starting process.

The other potential application of CHS is for the catalyst converters. The lower limit of optimal temperature (for purification performance) for a catalyst converter is 150^0C [4]. The temperature of exhaust gas immediately after starting the engine is around 100^0C, which is not enough for the operation of the catalyst. Because of this the efficiency of the catalyst at the low temperature is very low as shown in figure 3.

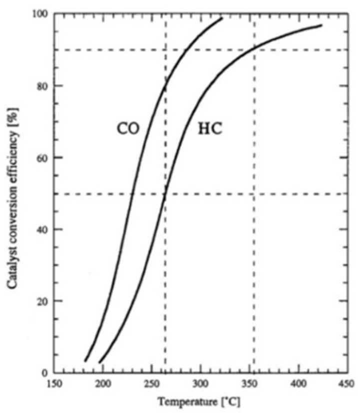

Figure 3: Dependence of catalytic convertor efficiency for HC and CO on temperature [5].

Beside the catalyst, the low temperature in the cold-start process affects the performance of the lubricant. In the low temperature, the viscosity of the lubricant increases, it makes the friction coefficient to decrease and reduction of the engine efficiency in cold start conditions.

In summary, for IC engine vehicles, The CHS technology can be applied to:

- heating the catalyst in the cold-start process.
- heating the lubricant in the cold-start process in the low temperature condition.
- defogging .

2.1 Applications of CHS in ybrid vehicles

Similar applications of CHS can be extended to hybrid vehicles. In the cold weather, a hybrid vehicle needsenergy for vehicle's climate control system. The energy of the exhaust gas of the IC engine can be utilized directly to increase the temperature in the cabin. However, the hybrid vehicle may need more energy stored for heating purpose in the cold weather.

Furthermore, the battery in a hybrid vehicle can be highly affected by low temperature. In the cold temperature, the change of the viscosity inside the battery (in the electrolyte) may lead to sluggish ion transport. The mobility of the ions decreases in cold temperature, causing a rise in internal resistance. The increase in the inside resistance of the battery leads to the lower battery performance.

In summary, in the cold weather, with the hybrid vehicles, CHS technology can be applied to:

- assisting vehicle's climate control system.
- heating the electrical battery.
- heating the IC engine or keeping it warm.

3 Experiments

Experiments were conducted on two engines: a gasoline engine (6-cylinder spark ignition Toyota Aurion engine at UTS engine laboratory, and a diesel engine (D1146TI engine equipped on buses in Vietnam) at Hanoi University of Science & Technology.

(a) (b)

Figure 4: Photos of the tested engines (a) Toyota Aurion, (b) D1146TI diesel engine.

Parameters	Unit	Gasoline engine	Diesel engine
Number of cylinders		6	6
Number of strokes		4	4
Bore	mm	94	111
Stroke	mm	83.10	139
Displacement volume	cc	3456	8071
Compression ration		10.8:1	16.7:1
Maximum power	kW	200@6200 rpm	151@2200 rpm
Maximum Torque	N.m	336@4700 rpm	735@1400 rpm

Table 2: The major specifications of tested engines.

The engine power is calculated based on the engine speed and torque. From the exhaust gas temperature and its components (were acquired by Horiba MEXA-584L gas analyser in the gasoline engine and the AVL test-bed in the diesel engine), heat loss is calculated by the summing the energy of components.

Properties	Unit	Gasoline engine	Diesel engine
Temperature	K	1028	704
CO	ppm	1000	31
CO_2	ppm	155000	50379
HC	ppm	9.9	183
NO_x	ppm	2335.7	1330
O_2	ppm	2000	98151
N_2	ppm	707714	806164
H_2O	ppm	130912	43762

Table 3: Data of the exhaust gas measurements.

The engine thermal efficiency and the heat lost in the exhaust gas were calculated with the experimental data. The exhaust gas energy was calculated based on the temperature and components of the exhaust gas. Heat energy of exhaust gases are the sum of the energy of components and are shown in figure 5.

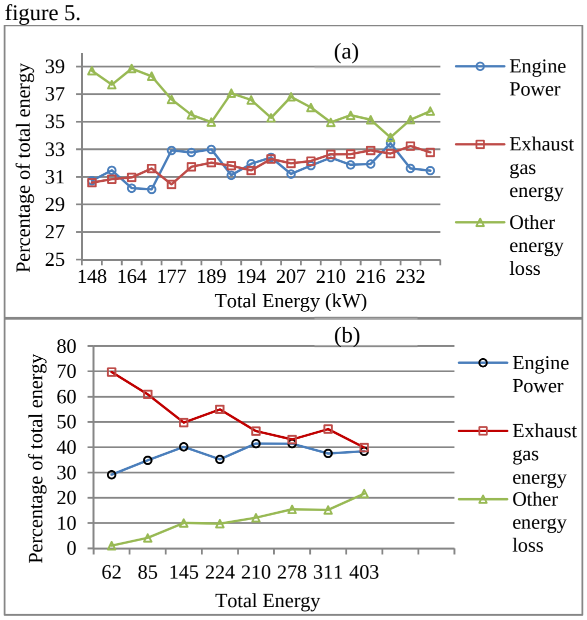

Figure 5: The energy consumption of gasoline engine (a) and diesel engine (b).

As shown in Figure 5, the energy loss due to the exhaust gas in the gasoline engine is smaller than that in the diesel engine. However, in almost operation conditions it is higher than 30%. In the diesel engine, in some condition the energy loss in the exhaust gas can increase to 70%.

4 Reactor design

Figure 6 shows the structure of the reactor designed based on the experimental results. The reactor consists of two tubes: inner and outer tubes. EM8 block is stored inside the inner tube, and the exhaust gas flows in the space between the two tubes.

Parameters	Unit	Value	Parameters	Unit	Value
Inner tube			Inlet, outlet and vapour ports		
Diameter	mm	100	Diameter	mm	88.9
Thickness	mm	3.05	Thickness	mm	3.05

Outer tube			Wings		
Diameter	mm	160	Thickness	mm	3.05
Thickness	mm	3.05			

Table 4: The dimensions of the reactor

In the heat storage process, the exhaust gas flows in the space between the two tubes from the inlet port to the outlet port while heat is transferred from the exhaust gas to EM8. With the heat energy provided by the exhaust gas, the dehydration reaction of $Mg(OH)_2$ takes place inside the inner tube. Water vapor from the reaction flows out of the reactor from the vapor port placed at the top of the reactor. In the space between two tubes, two wings are designed to make the temperature inside the reactor becomes even, and to increase the moving time of the exhaust gas flow in the reactor thereby to increase the heat transfer efficiency of the reactor.

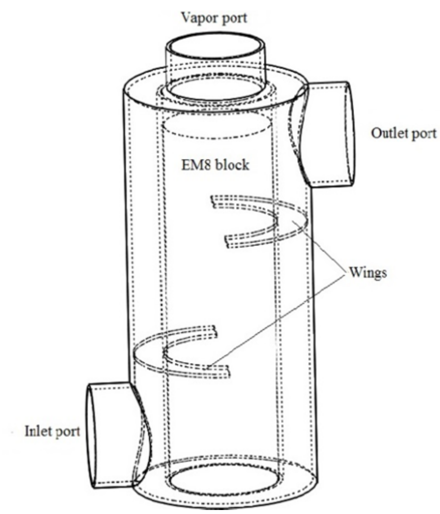

Figure 6: The reactor design

In the heat output process, the water vapor from the evaporator (water liquid is reheated by an electrical resister and evaporates at the evaporation pressure) flows to the reactor through vapor port. The hydration reaction is taken place inside the reactor and heat transfer from thermochemical material to fresh air through the inner tube wall. Low-temperature fresh air comes to the reactor at the inlet port, receives heat from thermochemical material and higher temperature fresh air moves out of the reactor at the outlet port to transfer to the heating system.

5 Simulation results of the heat storage process.

Simulation was performed to estimate the performance of the CHS and determine the dimensions. In simulations it was assumed that the reactor be placed right after the engine and in the heat storage process and that the temperature and the components of the exhaust gases at the inlet of the reactor be the same as that at the engine exhaust port. The measured volume ratios of the exhaust gases are listed in Table 3.

ANSYS Fluent was used to simulate the gas flows and heat transfer in the reactor. As the temperature of the exhaust gas at the engine exhaust port is high, the mixed thermal condition (combination of heat convection and radiation) model was chosen to simulate the heat transfer between the exhaust gas and the reactor walls. EM8 block is assumed as a solid material, so the heat transfer process inside the EM8 block is assumed as the heat conduction process with the properties given in table 1.

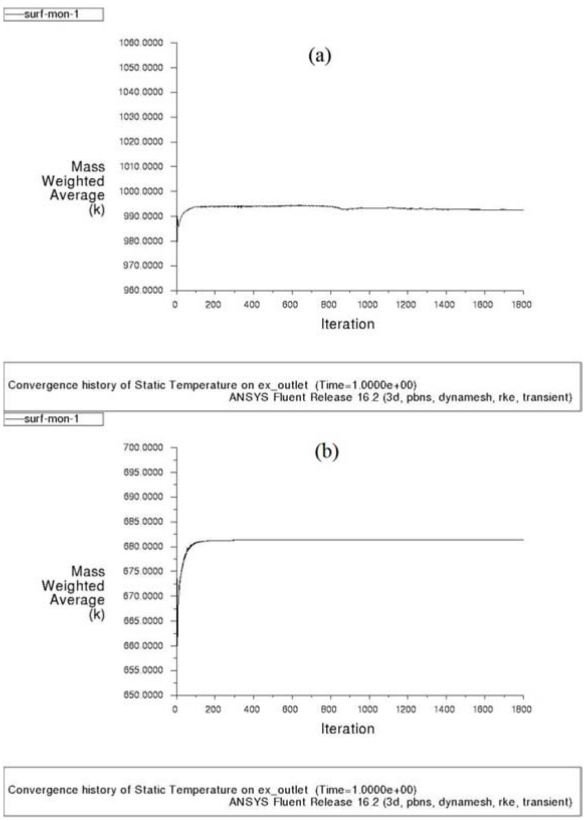

Figure 7: The temperatures of exhaust gas at the reactor outlet, (a) gasoline engine, (b) diesel engine.

As shown in figure 7, in the first 200s when the exhaust gas moves into the reactor, the heat energy of the exhaust gas is transferred to the reactor to increase the temperature of the reactor, the chemical material inside the reactor to a level required for chemical reaction. After that when the temperature of the reactor and chemical material becomes stable, the heat energy is 100% used for chemical reaction. The heat storage capacity of the chemical material is assumed as constant and so is the heat storage capacity of the reactor. This results in constant temperature of the exhaust gas at the outlet as shown in figure 7.

Based on the temperature of the exhaust gas, the heat energy of the exhaust gas at the outlet is calculated. The reactor is assumed as an insulated device so the energy stored inside the reactor is equal to the energy change of the exhaust gas between inlet and outlet of the reactor.

The efficiency of the reactor is defined as the percentage of heat energy of exhaust gas stored in the heat storage process. As shown in table 5, the efficiency of the reactor, 5.08%, in the gasoline engine is higher than that, 3.42%, in the diesel engine. The main reason is the average temperature of the exhaust gas of the gasoline engine is higher than that of the diesel engine. The reaction rate of the chemical material highly depends on its temperature. It increases with the increase of the temperature of the reaction material.

Properties	Unit	Gasoline engine	Diesel engine
Heat energy at the reactor inlet	kW	61.9	97.48
Temperature at the reactor outlet	K	991	681.5
Heat energy at the reactor outlet	kW	58.8	94.14
Energy stored in the reactor	kW	3.1	3.34
The reactor efficiency	%	5.08	3.42
Volume of EM8 block	dm^3	2.51	2.51
Mass of EM8 block	kg	2.51	2.51

Table 5: Energy storage in the reactor in the heat storage process.

The reaction of $Mg(OH)_2$ is only efficient when the temperature of the material is higher than 297^0C [6] (reaction temperature). With the diesel engine, at some low load conditions, the temperature of the exhaust gas is smaller than 297^0C and using magnesium hydroxide CHS system will be not efficiency in these cases. With gasoline engine, in almost operation conditions, the exhaust gas temperature is higher than 300^0C so using CHS system is efficient.

6 Conclusions

Using CHS system to store heat energy of exhaust gas is feasible with the efficiency of the gasoline and diesel engines are 5.08 % and 3.42 %, respectively with the same reactor and operation condition. The efficiency of the reactor in the gasoline engine is higher because its exhaust gas temperature is higher.

In some operation conditions, the temperature of exhaust gas of the diesel engine was lower than 297 ^{o}C which is the optimal temperature of $Mg(OH)_2$. The overall efficiency of the reactor in the diesel engine is low due to the low exhaust gas temeprature.

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