The Development of the Heat Storage Technology for the Automotive Waste-Heat Management

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ABSTRACT We have been developing a system in which waste heat from an automotive engine is stored during driving to warm up the engine oil, the transmission oil and others with the stored heat at a cold start. With the early warming up, the fuel efficiency can be improved because not only the combustion efficiency at a starting-up is improved but also because the friction loss of oil is reduced. Calcium oxide is typical as a heat storage material to make use of the heat in the temperature range of the exhaust heat. But, there is a problem that the device becomes large in size, because it is necessary to widen the surface area of the material to accelerate its reaction with the water vapor to gain a larger output. This is a barrier detrimental to the automotive use. We have been examining a compact heat storage system but with a high output and a high density which are realized with a combination of the heat-pipe technology and the heat storage material to make the material react directly with water (liquid) not with water vapor (gas). In our preliminary evaluation with a theoretical mock-up model, we have already got the data that shows that the heat output density was as high as double or more than that of the present heat storages.

1. INTRODUCTION

It is forecasted that energy consumption will be continuously increasing along with the expansion in the economy and the growth in the population in the world. Considering the global environment and the sustainable society, it is very important to shift to the renewable energy because most of the energy consumption at present depends on fossil fuel. In addition, it is also important to use energy at as high efficiency as we can do and reduce any waste or loss as well.

In the automotive field, the conversion from a vehicle with an internal combustion engine to an EV is expected to progress. However, the internal combustion engine is supposed to be continuously adopted to an HV and a PHV even after the year 2035[1)]. As for the internal combustion engine, only 30% of the total energy is used for driving power from the fuel because of its combustion efficiency and most of the rest is exhausted as an exhaust gas or a heat from a radiator into the atmosphere. On the other hand, at present, at a cold start, the heat energy is needed to warm up the engine, the oil and the emission control catalysts by burning an extra fuel to get the heat energy. Therefore, we think it will be a more efficient use of energy if we can use the stored heat for warming-up at starting-up, which was collected during driving instead of being exhausted into the atmosphere.

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2. THE TYPES AND FEATURES OF HEAT STORAGE MATERIALS

Typical materials used as the heat storage materials are shown in Table 1 along with their features. The technologies of heat storage are roughly classified into two types, one is the latent heat storage which involves the state change, and the other is the chemical heat storage which makes use of chemical changes. The method of latent heat storage uses the output and input of the thermal energy generated at the change of state between solid and liquid to store the heat. And its heat storage density is larger because the latent heat is added to the sensible heat. Its applicable temperature range is in the range from –20°C to 200°C. It is usually used for refrigerant (or ice packs) and for heat-retention material for floor heating. It is often used with a high-performance insulation because the heat is generally radiated outside over time. Such a system has ever been practically used where the coolant of a vehicle was kept in a thermos and used at starting-up[2)]. On the other hand, in a chemical heat storage system, the reaction heat is used, which is generated in the chemical reaction of combining a heat storage material with a reaction gas. Keeping the reaction gas separated from the heat storage material physically and mixing them to generate the heat when it is required. On the contrary, the state of the heat storage can be also maintained for a long period by keeping the chemical reaction from progressing, and the heat insulation structure is not necessary. Further, the chemical heat storage has a higher heat storage density by approximately 2 to 5 times than that of the latent heat storage and it is used at a high temperature range in the range from 100°C to 500°C[3]. In this development, considering its reaction speed and its reversible reaction characteristic with a high heat storage density, calcium oxide (CaO) has been selected. The selected material generates heat and absorbs heat in the heat reaction shown as $CaO+H_2O$ (gas)$\rightleftarrows Ca(OH)_2$ –109 kJ/mol.

Table 1 The types of heat storage materials.

Types of heat storage	Latent heat storage	Chemical heat storage
Principle of heat storage	Heat of state change (solid ⇔ liquid)	Chemical change (hydration reaction)
Typical materials	Sodium acetate trihydrate Sodium sulfate decahydrate Paraffin	$CaO+H_2O \rightleftarrows Ca(OH)_2$ $MgO+H_2O \rightleftarrows Mg(OH)_2$
Temperature range	–20 to 200℃	100℃ to 500℃
Advantages	Easy to design the heat exchange system	High heat storage density
Disadvantages	Low heat storage density	The device is large in size.
Applications	Uniform heating and applications of time difference heat ・Heat storage boards (in a capsule) ・Cooling mats (gel) ・Disposable heating pads (undercooling phenomenon) ・Heating and cooling in a building ・Defrost of a heat pump ・Freezers and air conditioning in a compartment	Very few examples in actual applications ・Air conditioning with waste heat Boosting for freezing ・Solar power generation and etc.

3. THE CURRENT TYPES OF HEAT ACCUMULATORS AND THEIR PROBLEMS

Figure 1 shows a basic structure of a current type chemical heat accumulator in general. It consists of a heat storage vessel in which a heat storage material is sealed, a reaction gas vessel in which a reaction gas is sealed, a flow channel made of pipe which connects those two vessels and a valve between them.

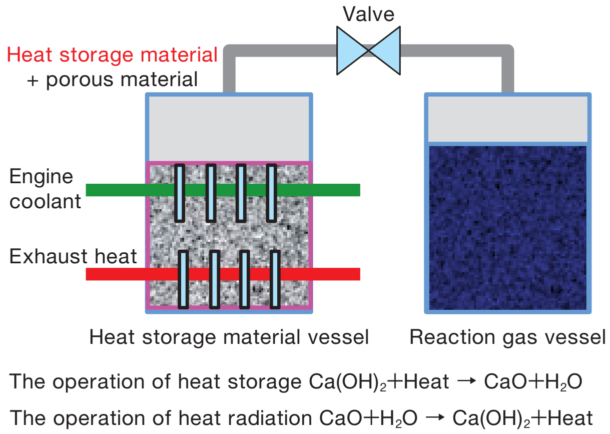

Figure 1 The typical chemical heat storage system.

The operation is explained of a CaO / H_2O system as follows. $Ca(OH)_2$ is filled in the heat storage vessel, the storage vessel is heated up, the dehydration is generated by cooling the reaction gas vessel, and the water vapor (H_2O) moves to the reaction gas vessel to condense into water and stay as water and vapor in the reaction gas vessel. If the valve is closed at the moment when the dehydration is finished, the separation of CaO from H_2O is completed. Returning the reaction gas vessel to normal temperature with keeping the valve closed after stopping the heating, the pressure in the heat storage vessel becomes negative and that in the reaction gas vessel becomes normal pressure (saturated water vapor pressure). Then, when opening the valve, water vapor moves to the heat storage vessel and reacts with the heat storage material to generate the reaction heat as a result. At the same time, in the reaction gas vessel, the evaporation of water is proceeding to remove the heat by the evaporation phenomenon and the temperature decreases. It is one of the features of this structure as well to generate this temperature gradient from the heat storage vessel to the reaction gas vessel[4].

However, a larger surface area for the reaction is required to accelerate the reaction between the water vapor and the heat storage material more efficiently. Therefore, in the system structure, the heat storage material has to be placed on the surface of corrugated fins used for a heat exchanger. As a result, the size of the heat storage vessel becomes much larger to be a major disadvantage to the system. Further, the reaction gas vessel is required to retain the water vapor itself because more amount of water vapor must react at once to get higher reaction speed. So, the size of the reaction gas vessel also becomes larger. Under the situation mentioned above, although the heat storage density of the material itself is as large as 2,000 kJ/L or more (converted into heat value per bulk), it would decrease to as small as 200 kJ/L or less, which is equivalent to the level of the latent heat material if it is considered as a heat storage device. This fact is a barrier against its use in the automotive.

4. A HEAT STORAGE DEVICE FOR AUTOMOTIVE USE

4.1 Target Values for the Automotive Use

Generally speaking, approximately 1 MJ is necessary as a heat value to warm up an automotive engine. Considering that the heat output density (density of heat per volume of vessel usable as heat) of the present type vapor reaction model is approximately 170 kJ/L (our estimated value), approximately 6 L each of the two vessels in volume is required. We think it represents a barrier against its use in the as mentioned above. In this development, we have been developing the heat storage device aiming at a target of two times higher heat storage density and heat output than those of a present-type heat storage device. The target values of this development were 500 kJ/L or more in the heat output density and 1.5 kW/L or more in the heat output, which are approximately as large as 2 times of present values[5], as the heat output density of present type of vapor reaction type is 170 kJ/L and the heat output is 0.7 kW/L. It was reported in the past that a heat storage system of the warm water thermos bottle type, which used to be integrated in the Prius of Toyota Motor Corp., had improved its fuel efficiency by 2% and its emission by 14% (at 25°C of LA#4 surrounding temperature) with a heat value of approximately 400 kJ. Therefore, based on this report, we estimated that the fuel efficiency would be improved by approximately 5% if we realized our target of the heat output density of 500 kJ/L and warmed up an engine with the device of 2 L in size[6].

4.2 A Loop-type Heat Storage Device

The heat storage material CaO originally generates 65 kJ/mol of its reaction heat in a combination with water (liquid) and retains a heat value of approximately 1,939 kJ/L (density 2.2 g/cm^3) converted into a heat value per bulk. The heat storage material must be in a powder shape, which will make the heat storage density much lower at once, because it will require a much larger surface area as mentioned above if it must react more efficiently against the water vapor. Therefore, we have examined whether the heat storage material is able to react against water (liquid), which is much smaller in volume. We have invented the structure practically shown in Figure 2, in which a Loop Heat Pipe (LHP) structure was adopted to repeat the dehydration and the heat generation reaction in the heat storage vessel stuffed with the heat storage material molded in compression.

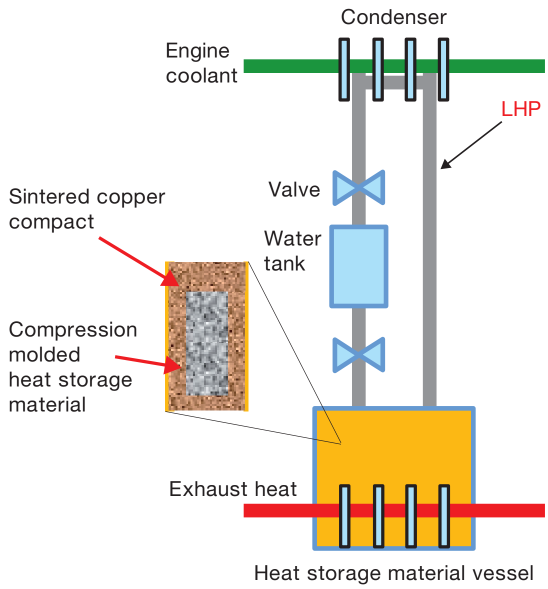

Figure 2 A chemical heat storage system with LHP.

The operation of heat storage is explained based on Figure 3 (a). When storing heat, the heat storage vessel is heated up under the condition where Valve 1 is open, but where Valve 2 is closed. The heated heat storage material causes the dehydration reaction to generate a water vapor and the water vapor becomes liquid in a condenser to be collected in a water tank. Closing Valve 1 when the reaction is finished, the heat storage is completed.

At the operation of heat radiation (shown in Figure 3 (b)), opening Valve 2 to feed water to the heat storage vessel, the reaction occurs to generate heat. Along with it, the heat storage material generates heat in the heat generation reaction. Then, feeding water more than the amount which is necessary for the reaction itself, some water vapors and this water vapor moves to the condenser and works as the LHP to be able to transport the heat to the condenser.

This device can operate as a heat pipe when radiating the heat. Therefore, the reaction heat generated in the heat storage vessel can be transported to any location on the heat pipe. It is the major feature of this system.

From the view point of the heat storage density, the reaction heat of the heat storage material CaO with water (liquid) is 65 kJ/mol as mentioned above and a heat value of approximately 1,939 kJ/L (density 2.2 g/cm^3) converted into the heat value per bulk is retained. 1,322 kJ/L is the attainable ceiling value of the heat storage density, as this device consists of the material molded in a compression of 1.5 g/cm^3.

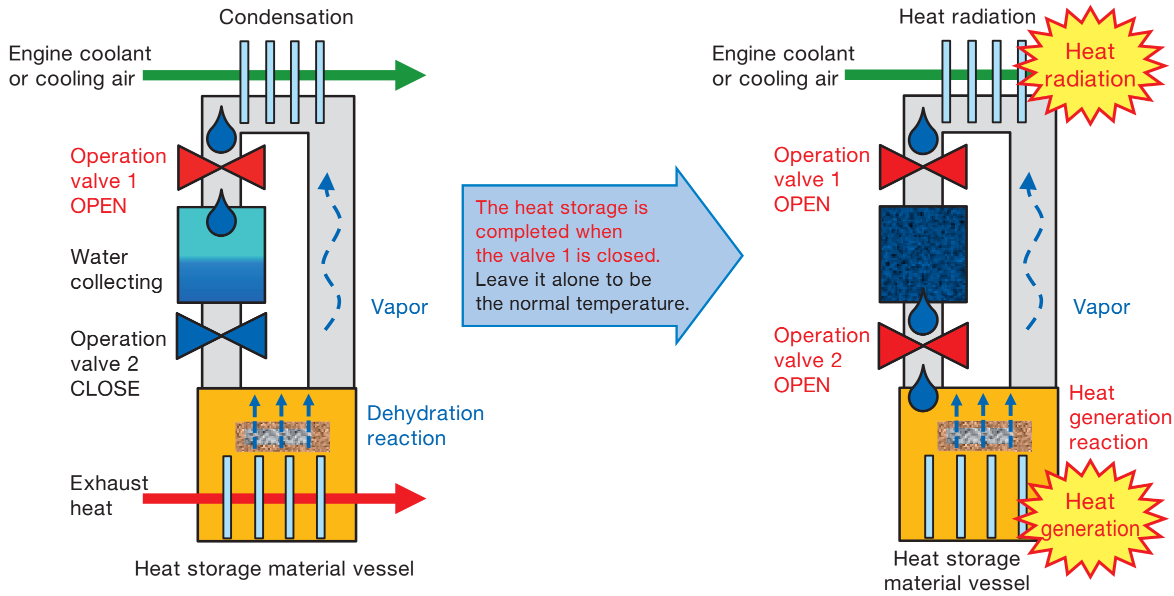

Figure 3 (a) Heat storage operation.

Figure 3 (b) Heat radiation operation.

4.3 The Experiment of the Heat Radiation

The temperature profile of the heat storage vessel when generating heat is shown in Figure 4. It indicates the increase of temperature at 3 positions of the vessel and shows that the temperature at the upper side of the vessel reached approximately 200°C in 30 seconds from starting the water supply. While the temperature at the upper side of vessel where water was continuously fed decreased but that at the center of vessel increased step by step to reach 300°C. Further, the profile of heat generation (per volume) is shown in Figure 5 and it is found out that the heat generation value reached 660 kJ/L in 300 seconds to confirm the target of no less than 500 kJ/L was reached. And, it succeeded in achieving such a high output as the average heat output of 2.2 kW/L for a duration up to 300 seconds. This result means that 77% of the heat value was collected compared to the theoretical value because a theoretical calculation of heat storage density based on the material quantity in this heat storage vessel has resulted in 853 kJ/L.

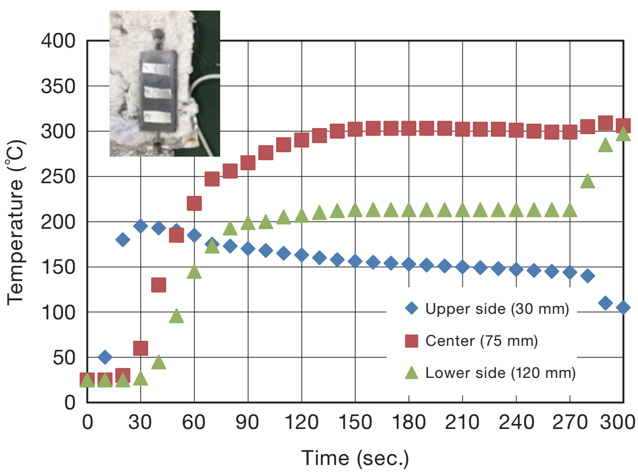

Figure 4 The changes of the temperature in the heat storage vessel.

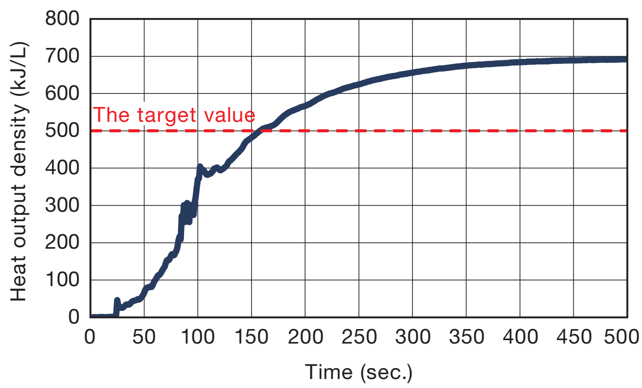

Figure 5 The changes of the heat output in the heat storage vessel.

The temperature profile of the heat radiation at the condenser on the LHP is shown in Figure 6. The increase in temperature was reached in 100 seconds after the starting of the water supply. The heat output density and the heat output were 385 kJ/L and 1.3 kW/L respectively. We thought it might be caused by the influence of the heat capacity (shown in Figure 7) of the pipe where the heat value and the heat output at the condenser were much smaller than those at other positions in the heat storage vessel. It is one of our themes today and in future to improve the efficiency of the heat utilization such as shortening the pipe from as long as 1 m and to reduce the thermal capacity.

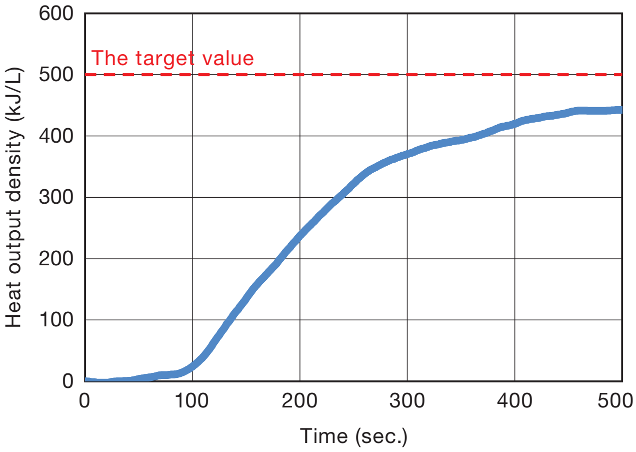

Figure 6 The heat output at the condenser of LHP.

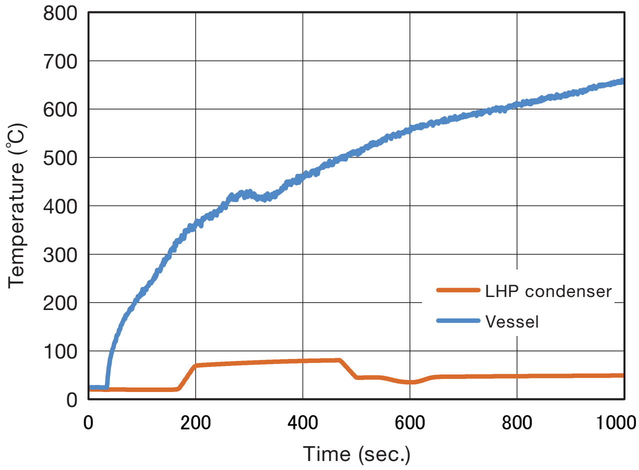

Figure 8 The temperature at the condenser during the heat storage.

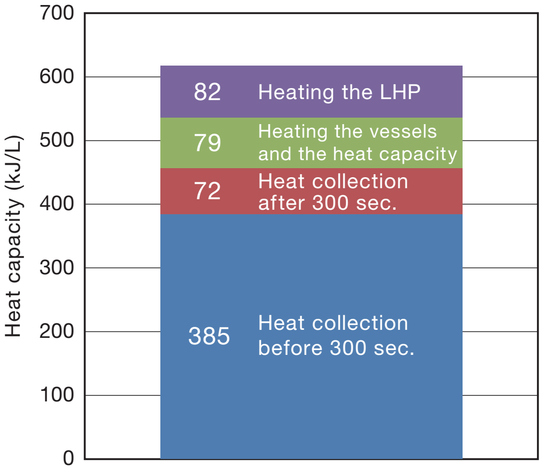

Figure 7 The breakdown of the total heat value.

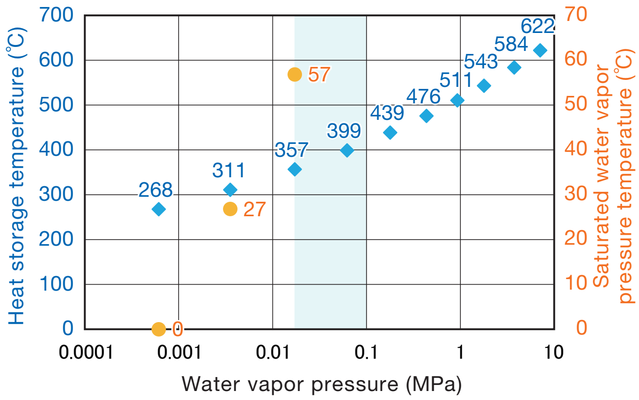

Figure 9 Calculated values of the dehydration reaction of calcium hydroxide $Ca(OH)_2$.

4.4 An Experiment of Heat Storage

The change of temperature when storing the heat is shown in Figure 8. It shows that the temperature of heat storage vessel was continuously increasing to 350°C (180 seconds) and around it, the temperature at condenser started to increase. In this state, it is estimated that the water vapor started to condense, and that the behavior of the temperature was caused by the dehydration of the heat storage material. As the temperature at the condenser returned to the previous one in approximately 500 seconds, it can be considered that the dehydration was terminated, and that the heat storage was completed. Figure 9 shows the relation between the pressure (saturated water vapor pressure) in the LHP, the dehydration temperature and the water vapor temperature (calculated). Then, it can be found that the dehydration temperature was 357°C when the saturated water vapor pressure was 17 kPa at 57°C of the condenser temperature (the water vapor temperature). As a result of this experiment, the data also proves what was mentioned above.

5. CONCLUSION

We have built a mock-up model of the loop-type heat storage device containing the heat storage material in a part of the LHP. And, we have confirmed as a result of our experiment that the heat output density of 660 kJ/L, which was larger than the target value of 500 kJ/L and the heat output of 2.2 kW/L could be produced. The heat radiation at the condenser by heat transportation was no larger than 385 kJ/L, but the possibility of heat transportation itself was positively confirmed. We have concluded that we have indicated the possibility to make use of the waste heat used with our device which is different in concept from the present-type chemical heat storage device. Further, we have discovered in this experiment a problem where a considerable quantity of heat radiation was lost in a long heat transportation time caused by a large heat capacity up to the condenser. From now and in future, after checking the repeating durability, the starting performance under low temperature and so on, we are planning to examine the application to actual vehicle warming-up system (applications are shown in Figure 10).

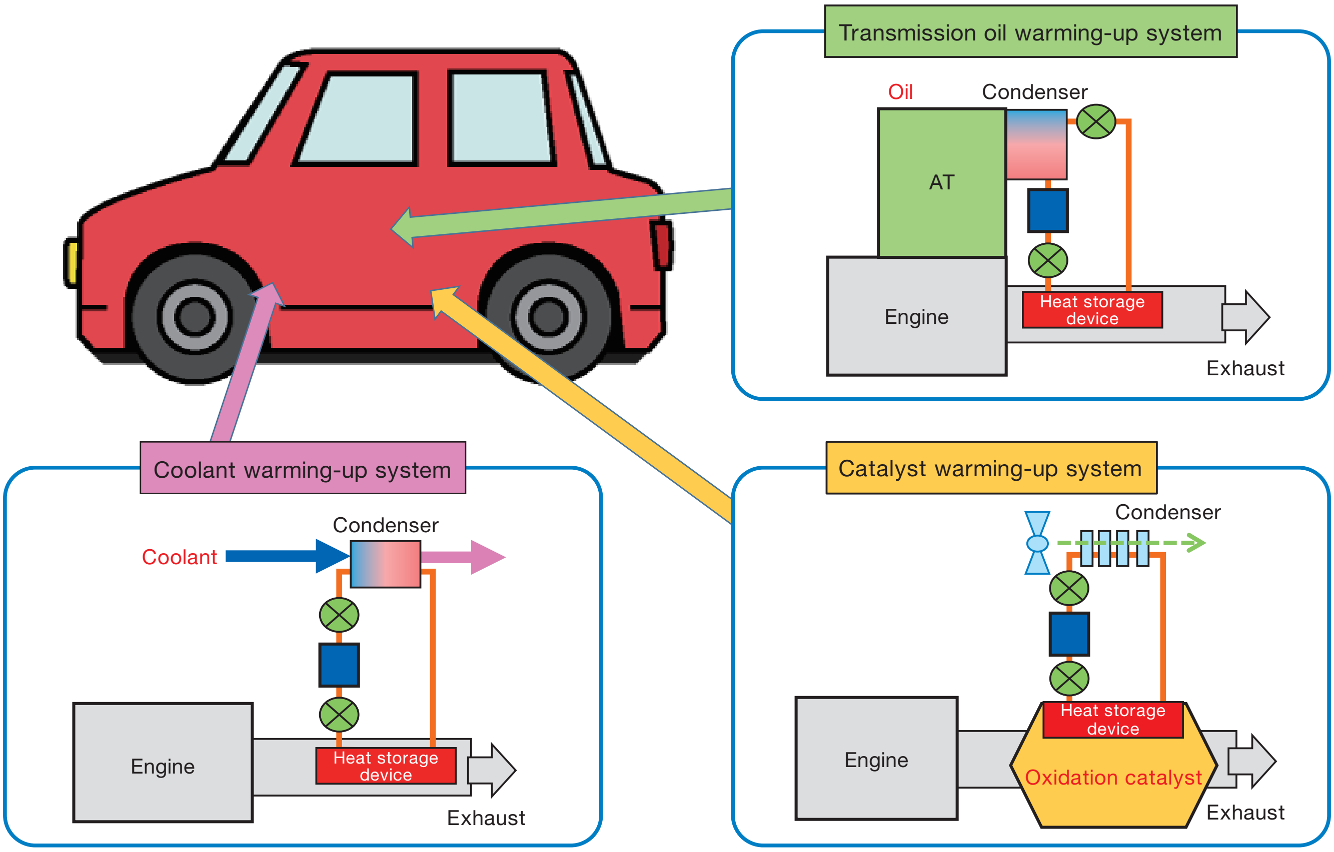

Figure 10 Application examples to the warming-up system.

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