Study Of A Latent Heat Storage Battery With Phase Change Material And Its Application

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***Abstract*—Latent heat energy storage is an efficient solution for reducing fuel consumption of an engine by using its wasted energy. In this study, NACOL 22-98, a Phase Change Material (PCM), is used. On a first step, the storage tank was installed on an experimental setup to characterise its efficiency. Electrical resistances are used to heat up the water flowing into the tank. On a second step, a model of the storage tank is developed on GT-Suite and is calibrated with the experimental results. Finally, the storage tank is installed on a 3-cylinder Gasoline engine test bench, downstream the cabin heater. The results show an improvement of 13°C during the warm-up of the engine.**

Keywords—Thermal management; Phase change material; Latent heat storage; Cold start; Internal combustion engine

I. Introduction

To answer the different emissions regulations, research on internal combustion engine is focusing on increasing the engine efficiency and reducing its emissions. The engine tends to consume more fuel and produce more pollutants during cold start phase. Those aspects can be reduced by improving the engine warm-up phase. In addition to that, during the steady state of the engine, around 66% of its energy is lost in form of heat either with the exhaust gas or transferred to the coolant.

Latent heat energy storage is based on the heat absorption or heat release when a material undergoes a phase change from liquid to solid or vice-versa. Heat from the engine can be recovered during its steady state either from the exhaust gas or from the hot coolant. The Phase Change Material (PCM) chosen should have the following proprieties [1]:

- Thermal proprieties: the PCM should have a matched melting/solidifying temperature with the application, a high latent heat and high thermal conductivity.
- Physical proprieties: phase stability and small volume changes on phase transformation.
- Chemical proprieties: PCMs should be non-toxic, non-flammable and non-explosive.
- Economics: Low cost and large-scale stability.

Kim *et al.* [2] compared different types of PCM in function of their melting temperature in a form of graph. The melting temperature ranged between 60°C and 200°C. PCM with the melting temperature between 60°C and 100°C can be used in the coolant circuit. However, those with higher melting temperature are more suitable for the exhaust line [3]. Schatz used a Water/salt mixture which stores heat when melting. In his study, the heat battery with a capacity of 600 Wh, when cooled down from 80°C to 50°C, was used for defrost, defogging and warming up the cabin. Gumus [4] presented in detail his storage tank and stated that charging and discharging the later take 500s and 600s respectively. In addition to its heat battery, two valves, an electrical pump and a control system were added to the system. However, Vetrovec [5] located its storage tank downstream the radiator thus eliminating the use of other valves than thermostat. The Vetrovec system is well described in [6]. Reverault *et al.* [7] assessed the latent heat storage on the coolant and the oil circuit. The battery was surrounded by vacuum insulation and its volume was 4L and weighted 8kg when used with the coolant. He stated a 6% of fuel savings when applying Artemis Urban. Park *et al.* [8] assessed the PCM on a Diesel engine by measuring the performance of the heat accumulator, the durability of PCM and its effects on the engine. They stated a reduction of the warm-up time between 18.1% and 27.1% depending on different conditions. Moreover, a numerical study of the latter experimental setup was presented by Park *et al.* [9].

Shon *et al.* [10] study consisted of improving the heat storage rate and efficiency of a heat exchanger filled with 4.2 kg of PCM. They stated that the coolant flow rate has a higher influence on the absorption efficiency than the coolant temperature. Their experiments showed an improvement of 33.7% in the warm-up time of the engine. Similar to that, Yang *et al.* [11] focused on the heat exchanger enhanced by copper foam and fin filled with PCM to improve its efficiency. Kim *et al.* [2] designed a down-sized prototype with a heat accumulator containing the PCM and succeeded to reach a higher temperature of the coolant by 25°C compared to the full size system. Roberts *et al.* [12] made a developed review over the latent heat storage application on different engine systems and discussed the challenges and issues of using PCMs. Other reviews were made by Zalba *et al.* [13] and Agyenim *et al.*[14]. PCM were used on

(a) (b) (c)

Fig. 1. Thermal battery

batteries in the electric and hybrid vehicles [15]–[17]. Other applications of PCM were in the vehicle body where inserts of PCM were introduced to enhance its thermal comfort [18].

In this work, a phase change material will be presented, and a latent heat energy battery will be characterized on an experimental setup. A GT-model of the heat battery will be presented and calibrated using the experimental results. Later on, the thermal battery is installed on a 3-cylinder turbocharged gasoline engine and tested over different driving cycles. Results of the warm-up and the soak period of the heat battery will be presented. Also, different plot of the model will be showed as well as the results of the engine test bench.

II. Experimental Setup

A. *PCM selection*

Phase change material uses their melting and liquefaction process to store and release heat in a constant temperature range. A large variation of PCM exists on the market and they are divided by their melting point that can go from negative temperature and reaches very high temperature depending on the composition of the material. Therefore, the melting temperature is an important criterion when choosing a certain PCM for an application. For an internal combustion engine and an application on its coolant circuit, this criterion should be close to the temperature of the steady state of the engine which is around 90°C in this study and not higher. The PCM around this temperature are mainly fatty acids, paraffin and salt hydrates. Further, other characteristics of the PCM are important and should be taken into consideration. The PCM chosen should not react with the environment material surrounding it and it should have a long life time and a low degradation through the phase change cycles. In internal combustion engine application, and for the security of the passengers, the PCM should be non-flammable and neither toxic or corrosive. With higher latent heat value, the storage of the material will be more important. Also, a good thermal conductivity reduces the temperature gradient in the storage battery and accelerates the heat exchange with the engine coolant. As well, the density of the material in two phases solid and liquid should not be very different to prevent the higher volume expansion.

NACOL 22-98 was chosen for its different characteristics as shown in TABLE 1.

TABLE 1 - PCM CHARACTERISTICS

PCM	***NACOL 22-98***
Melting temperature (°C)	69
Latent heat (kJ/kg)	250
Specific heat capacity (kJ/kg.K)	3
Density solid/liquid (kg/m^3)	0.8
Thermal conductivity (W/m/K)	0.2

B. *Test Bench*

4 Kg of PCM (5L in the liquid state) are introduced in a storage battery. The PCM surrounds a helical tube in which flows the engine coolant. Fig. 1 shows the inside of the thermal battery (Fig. 1– (a)), the initial state of the PCM (granular form) (Fig. 1 – (b)), and the PCM state after the first use (**Error! Reference source not found.** – (c)).

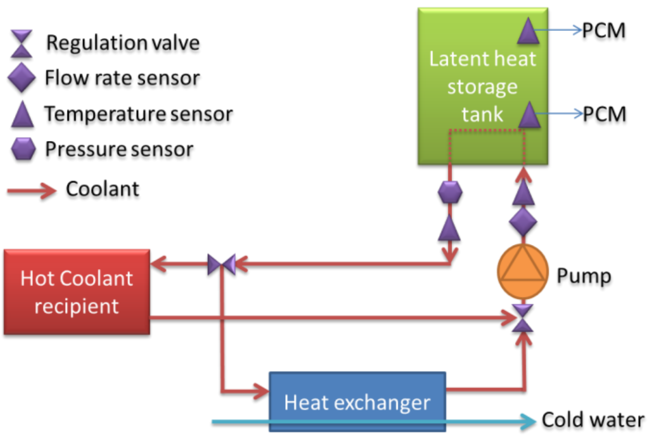


Fig. 2. Schematic presentation of the experimental setup

The latent heat storage battery was installed on a test bench to characterize its heat exchange as well as the pressure drop. The experimental setup (**Error! Reference source not found.**) is divided between two circuits: hot and cold. The hot circuit is a closed loop composed of a 12V Bosch pump, the latent heat storage tank, a coolant volume and different sensors. The coolant volume is heated with four electrical resistances of 2 kW each. Downstream the pump, a variable area flow meter H250 M40 is installed to measure the coolant mass flow rate. The cold circuit is composed of the same pump and coolant flow meter. However, after the storage battery the coolant flows into a heat exchanger to be cooled down. The cold source is around 20°C. The two circuits are separated by several two-way valves.

The coolant temperature and pressure at the inlet and the outlet of the storage tank are measured using K-type thermocouples and OPTIBAR P 1010C sensors respectively. Two other k-type thermocouples are installed in the storage tank to have the temperature of the PCM. One of the sensors is located at the center of the tank while the other is near the surface. Different sensors characteristics are presented in TABLE 2.

TABLE 2 - SENSORS CHARACTERISTICS

Sensor	***Calibrated range***	***Accuracy***
PCM and Coolant temperatures (K-type thermocouple)	0-1000 °C	± 1°C
Coolant pressure (Khrone Optibar P 1010 C high temperature)	0-2.5 bar	± 0.25%
Coolant mass flow rate (Khrone H250)	6-60 L/min	± 1.6%

Various tests are done. Firstly, heating and cooling the tank are registered using different coolant flow rate ranging between 12 and 18 l/min. The Flow rate range chosen covers the coolant flow rate in the heater branch of the engine. For the heating tests, the hot circuit was used. Once the PCM melts down and in its liquid phase, the cooling test takes place and the cold circuit is used. Secondly, soak test of 15 hours is performed. The battery is heated to 85°C and it was left over 15 hours to cool down with simple heat loss to the ambient. This second test evaluates the insulation efficiency of the battery.

After different tests, it is noticed that the thermocouple used to measure the PCM temperature near the surface was not fixed perfectly and it was moving from a test to another. For that the results obtained by this sensor are not considered credible. The results for the different PCM temperature that are close to the helical tube for different coolant flow rate are presented in **Error! Reference source not found.**. PCM temperature for the 18L/min test are registered from the beginning while for the other two tests recording starts when the PCM attended around 40°C. The melting point of the PCM can be seen in the change of the slope of the different plots. It starts around 67°C and it takes place around 356s for the blue (12L/min) and red curve (14L/min) and around 736s for the yellow curve (18L/min). The PCM was kept at 86°C for a period of time to ensure that all the storage tank was melted and that the same temperature was reached by the outer thermocouple. During the cooling phase, the water flowing in the circuit is around 20°C.

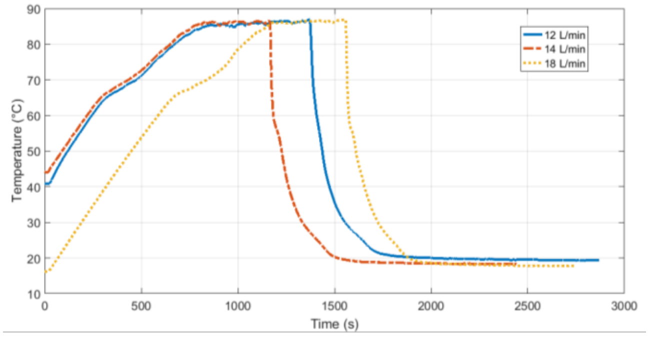


Fig. 3. PCM temperature behavior

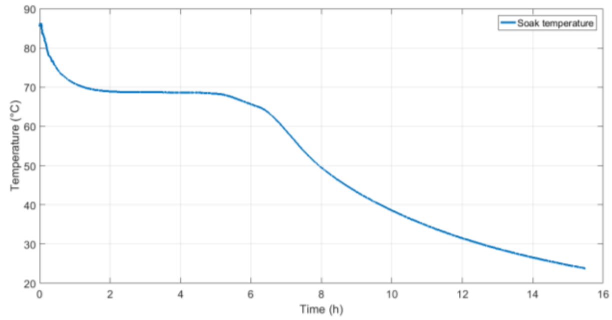


Fig. 4. Soak temperature over 15 hours

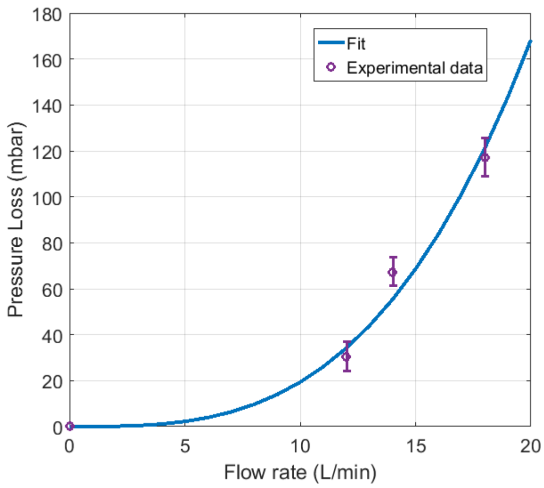


Fig. 5. Pressure drop of the storage tank

The overnight cooling test is presented in **Error! Reference source not found.**. For the soak period, the 0-flow concept was applied. The pump is shut down and no water circulates into the storage tank, thus no forced convection takes place between the water and the PCM. The fusion transformation of the material is well underlined in this experimental setup. Once the temperature of the PCM reaches around 69°C, the liquid PCM starts releasing its heat to the ambient environment and solidifies during a period of 3.4 hrs. The ambient temperature varies during the night with an average of 13°C. The thermal tank is stored in a non-insulated area of the test lab.

Error! Reference source not found. depicts the coolant pressure drop in the thermal storage tank. It is minimal at the lowest flow rate of a value around 30 mbar and it rises to around 113 mbar at 18 l/min.

III. PCM MODEL

A 0D-model of the thermal battery was developed on GT-Suite using the basic library in the software. The calibration of the model is divided into two parts. The first one consists of calibrating the heat exchange or loss to the ambient environment using the soak period experimental data. While the second one is about the heat exchange with the coolant based on the data of the three experimental tests with the different coolant flow rates.

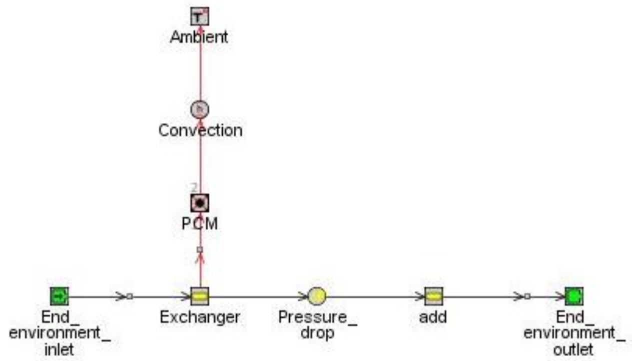


Fig. 6. PCM model

The model presented in **Error! Reference source not found.** consists of the main following components:

- Two end environments which are used to set the boundary conditions of the coolant in the system: Temperature and flow rate.
- A homogenous thermal mass representing the PCM. It is characterized by its mass, its initial temperature as well as the properties of PCM.
- A convection model that connects the thermal mass of the PCM to the ambient environment.
- A tube to represent the coolant in the thermal battery and to define the thermal exchange between the two fluids.
- A pressure drop model.

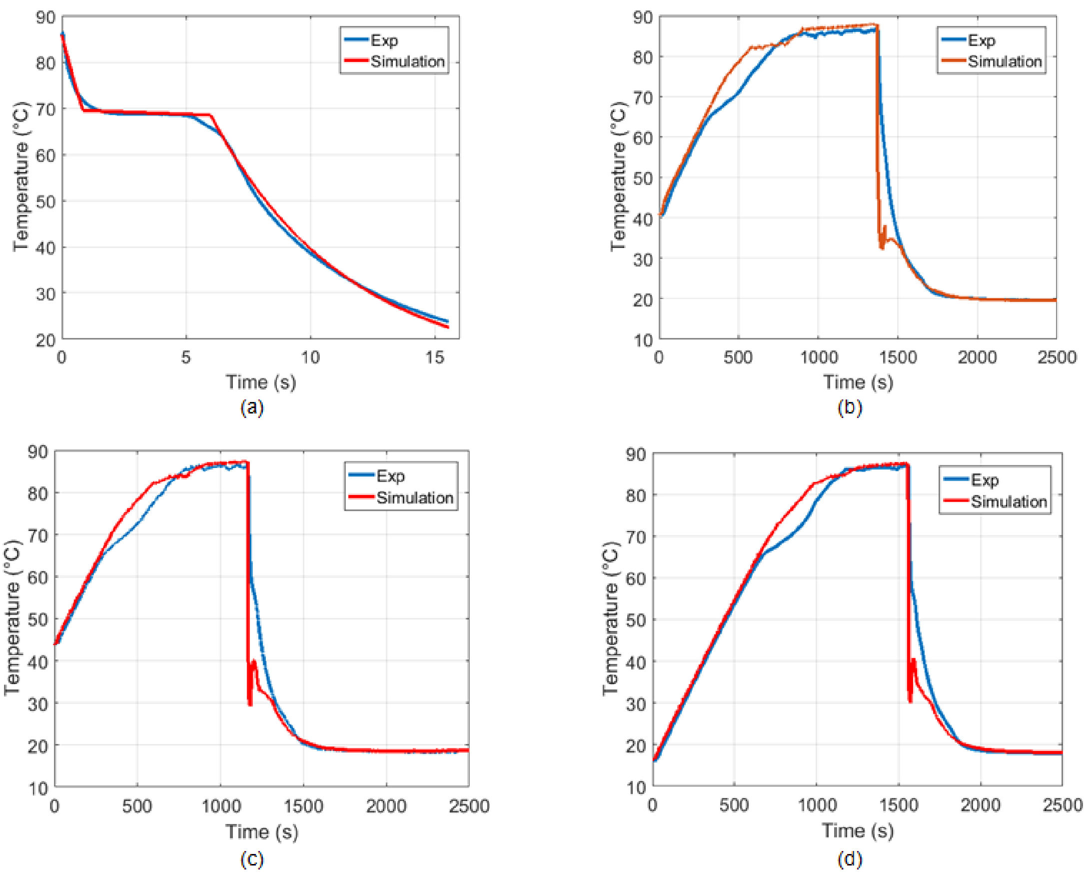


Fig. 7. PCM model results

The boundary conditions (Temperature, Pressure/flow rate) of the coolant and the ambient are set in the model as well as the characteristics of the PCM, geometrical dimensions of the tank. The outcomes are compared to the experimental data to validate the model.

During the soak period, the heat losses of the thermal battery are not limited to the ambient air. The coolant which is trapped in the experimental setup exchanges heat with the PCM mass. However, it is complicated to assess the latter and to model it. For that, the thermal losses to the ambient were overestimated in a way to recover the heat loss to the coolant. To do that, two parameters which are the convective heat transfer coefficient (h) and the surface area of the heat exchange(S) are controlled. The results obtained are presented in **Error! Reference source not found.** – (a). The simulation results (the red curve) agree with the experimental one (the blue curve). The highest difference in the soaking period is around the end of the solidification phase, it reaches 2.9°C. In addition to that, a difference between the experimental results and the simulation during the liquid phase is observed. The red curve is closer to a linear form.

The same methodology is applied to calibrate the heating process with the different flow rates. The boundary conditions of the coolant are imposed to the model and the outcome of the temperature is compared. The results are depicted in the part (b) – (c) and (d) of **Error! Reference source not found.** for respectively 12 L/min, 14 L/min, and 18 L/min as coolant flow rate. The experimental and the simulation curve are very close in the three cases. The red curve departs from the blue one at the beginning of the phase change of PCM. This change of slope is not present in the model because the latter is a basic model with one homogenous mass representing the 4 kg of PCM in the storage battery. Therefore, conductivity and temperature difference in the thermal storage tank are not present in this model.

IV. Application On An Engine

A. *Engine Test Bench*

To assess the potential of the battery on a powertrain application, it is coupled to an internal combustion engine (**Error! Reference source not found.**). The work is done on a three cylinder downsized turbocharged direct injection engine. The specifications of the engine are given in the **Error! Reference source not found.**. The gearbox was replaced by a direct drive to the dynamometer. Two big ventilators blow air on the radiator and on the charge air cooler. They are controlled to simulate the same effect of a driving cycle. Pressure and temperature are measured all along the inlet and the exhaust line. Similar to that, rotational engine speed, torque, fuel consumption and turbocharger speed are also recorded. A lambda sensor is used to calculate the air fuel ratio.

The storage battery is installed on the cabin heater branch of the engine. A bypass of the battery is added to the configuration (**Error! Reference source not found.**). The battery is bypassed when the engine coolant temperature is higher than the PCM temperature. The electrical resistances are used to heat up the storage tank and melt down the PCM. When the temperature of the storage tank reaches 80°C the hot recipient is bypassed and the tank is connected to the engine coolant circuit.

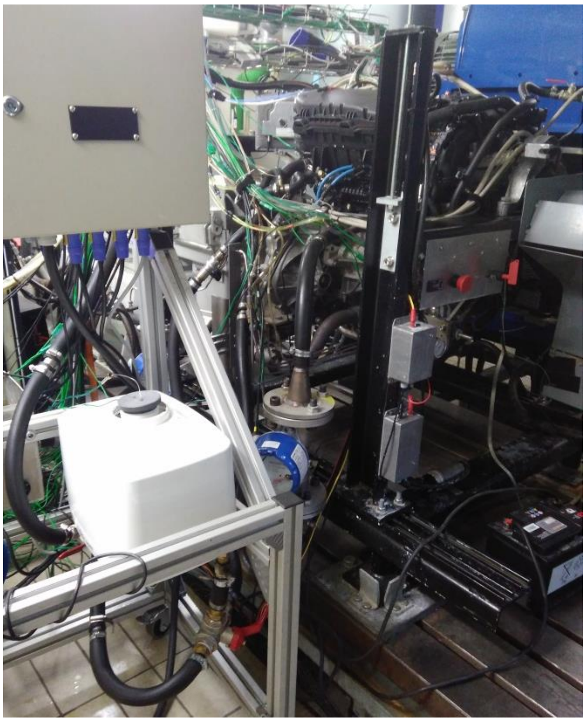


Fig. 8. The thermal battery installed on the engine test bench

TABLE 3 - ENGINE SPECIFICATIONS

Engine type	Direct injection
Fuel	Gasoline
Cylinder	3 cylinders
Displaced volume	1.2 L
Turbo charging system	Waste gate
Bore	75 mm
Stroke	90.5 mm
Compression ratio	10.5 :1
Number of Valves per cylinder	4
PME max at 1500 RPM	24 bar

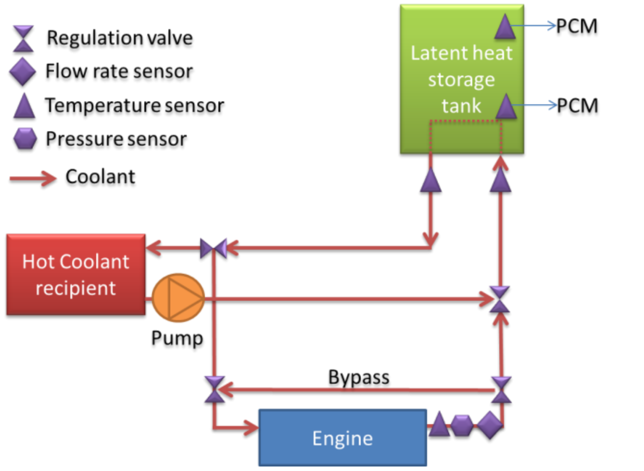


Fig. 9. Schematic presentation of the thermal battery on the engine test bench

The different tests on the engine test bench are divided into two parts:

- The reference tests: the engine runs two cycles without the PCM.
- The assessment tests: the engine runs the both cycles but with the thermal battery heated up to 80°C.

The two driving cycles are WLTC and HDC. The latter is an in-House Developed driving Cycle developed to highlight the application of different thermal management strategies. This cycle is developed and explained in Sara et al. [19] work and presented in **Error! Reference source not found.**.

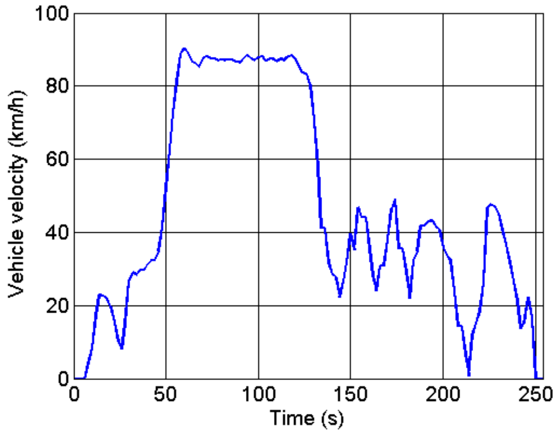


Fig. 10. in-House Developed driving Cycle

B. WLTC

The main results of the experimental setup for a WLTC are presented in **Error! Reference source not found.**. The solid line represents the results of the reference tests for the coolant and the lubricant temperatures with the blue and the red lines respectively. The dotted lines are the results of the assessment test with the storage battery connected to the engine.

The improvement in the temperature profile of the two fluids is remarkable at the start of the cycle. The temperature profile with the PCM starts lower than the reference one. It is because of the added volume of coolant to the system. However, quickly this temperature rises to higher than the reference case. The thermal battery is bypassed once the temperature of the coolant at the outlet of the thermal battery is equal at the coolant at the outlet of the engine (no more heat is transmitted to the coolant). The shift between the thermal battery and the bypass is done manually with a 2 way valve as depicted in **Error! Reference source not found.**. The time between the decision making and the valve switching is around 10 seconds maximum. For WLTC, the storage tank is bypassed around 180s of the cycle. Further, the coolant curve starts converging to the reference case. The coolant and the lubricant exchange heat at the oil cooler. Because the coolant temperature is getting higher, the heat transfer between the two will be higher and it will cause the temperature of the lubricant to be improved during the warm-up phase. Improving the lubricant temperature will lead to a reduction in the power losses due to the friction and thus reducing the engine fuel consumption. The same behaviour for the coolant and the lubricant temperatures are observed (**Error! Reference source not found.**). The highest temperature difference on the coolant temperature curve is 13°C at 150s. On the lubricant side, the highest difference between registered is around 11°C at 100s. TABLE 4 indicates the gain in time to attend the following temperature: 50°C, 70°C and 90°C for the coolant and the lubricant when the storage tank is connected to the engine. The coolant takes twice the time to reach 50°C without the thermal battery.

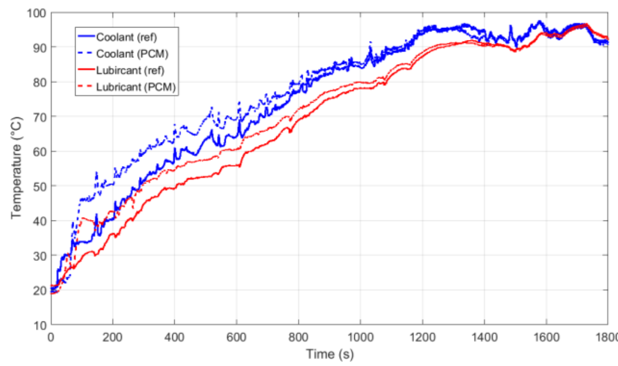


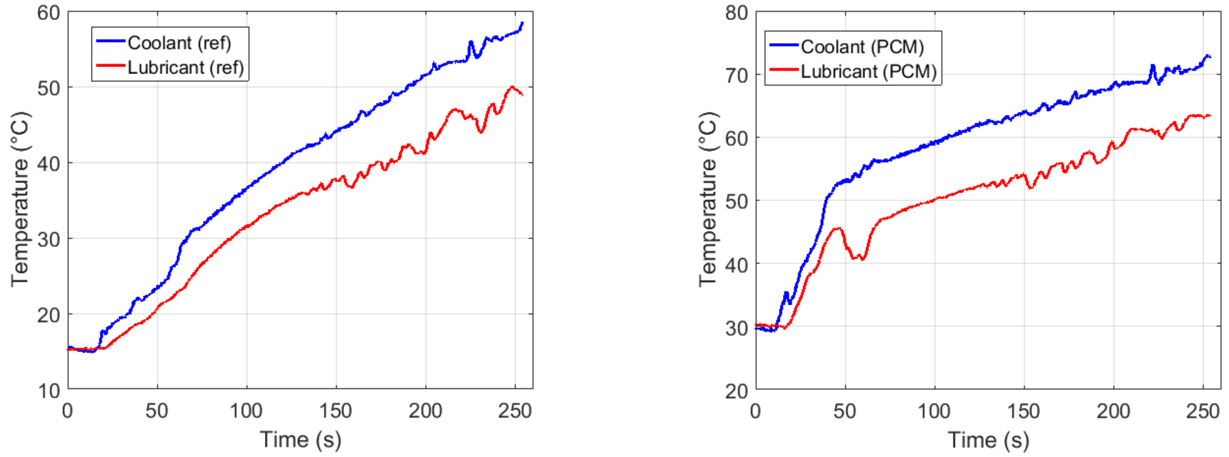
Fig. 11. Temperature profile evolution during WLTC with and without PMC

TABLE 4 - TIME GAIN IN SECONDS TO REACH THE INDICATED TEMPERATURE WITH THE STORAGE TANK

Time to reach	*50°C*	*70°C*	*90°C*
Coolant	143s	178s	13s
Lubricant	110s	36s	42s

C. in-House Developed Driving Cycle (HDC)

The main results for HDC are presented in **Error! Reference source not found.**. Despite the difference in the initial temperature, the slope of the temperature profile shows the improvement with the thermal battery installed on the test bench. With the thermal battery, the slope of the coolant and lubricant temperature are much steeper.



(a) (b)

Fig. 12. Temperature profile on HDC without (a) and with (b) PCM

The coolant gains 25°C within 54s. While the same evolution of 25°C, at the start of the cycle for the reference case, is reached after 120s. However, the temperature difference of the coolant between the end and the start of the cycle is quite similar for the two cases because of the tendency of the coolant temperature to converge to the reference case as it happened with WLTC. The lubricant temperature shows a drop in temperature around the highest acceleration in the driving cycle.

V. Conclusion

A storage tank with 4 kg of a phase change material was installed on a test bench to characterize its thermal behavior. Temperatures and pressures of the coolant at the inlet and the outlet of the battery were registered as well as the temperature of the PCM. Two sets of tests were done to characterize the charge of the battery with a hot coolant and the soak temperature during 15hrs. The data issued from the experimental tests were used to calibrate the battery model which was developed on GT-Suite. Results showed good agreement between the numerical simulation results and the experiments. The maximum error found during the soak period between the simulation results and the experimental tests was 2.9°C. To assess the potential of the thermal battery, the latter was installed on the heater branch of a 3-cylinder gasoline. It was tested over two different driving cycles: WLTC and HDC. The latter is an in-house developed driving cycle proposed to highlight the different thermal management strategies. The result of the test bench shows a remarkable potential of the thermal battery by improving the temperature of the coolant during the warm-up. An improvement of 13°C was registered at 150s after the start of the WLTC. The improvement in the coolant temperature leads to an improvement in the lubricant temperature which registered a difference of 11°C at the 100th second of the cycle. Reaching 50°C for the coolant was faster by 143s with the thermal battery installed on the engine for a WLTC. For HDC, an evolution of 25°C of the coolant temperature was reached within 54s with the thermal battery while it took 120s without it.

This study underlines the potential of the latent heat storage with PCM on a Gasoline engine. Therefore, the next step is modeling the battery in the engine environment to study different configurations of the battery as well as different ambient conditions. In addition to that, a conception study of the battery, its insulation and its feasibility could be interesting.

Acknowledgment

The work in this article is done in a joined International Teaching and Research Chair entitled “Innovative Intake and Thermo-management Systems” between MANN+HUMMEL and Ecole Centrale de Nantes.

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