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Temperature optimisation of a diesel engine using exhaust gas heat recovery and thermal energy storage (Diesel engine with thermal energy storage)

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Keywords

Diesel engine

Heat recovery

Thermal energy storage

Phase change materials

Cold start emissions

Fuel economy

ABSTRACT

Modern automotive diesel engines are so energy efficient that they are heating up slowly and tend to run rather cold at subzero temperatures. The problem is especially severe in mail delivery operations where the average speed is low and the drive cycle includes plenty of idling. The problem is typically solved by adding a diesel fuelled additional engine heater which is used for the preheating of the engine during cold start and additional heating of the engine if the coolant temperature falls below a thermostat set point during the drive cycle. However, this additional heater may drastically increase the total fuel consumption and exhaust gas emissions of the vehicle. In this study the additional heater was replaced by a combination of exhaust gas heat recovery system and latent heat accumulator for thermal energy storage. The system was evaluated on a laboratory dynamometer using a simulated drive cycle and in field testing in the city of Oulu (65 °N), Finland in February 2009.

1. Introduction

Improvement of fuel economy and reduction of exhaust gas and particulate emissions are key development items for automotive internal combustion engines. Diesel engines are typically more efficient than gasoline engines and therefore preferred for professional use like mail delivery operations where fuel economy is an important cost factor. It is well known that a great deal of exhaust gas emissions occur during cold start [1-3] especially in cold climates. These can be avoided by proper preheating of the engine. The preheating can be realised using an electric or a diesel or gasoline fuelled engine preheater or by using thermal energy storage (TES) to store excess heat of the engine to the next cold start. The TES can be realized by storing the sensible heat of extra coolant in a well insulated thermoflask [4] or by using a latent heat accumulator (LHA) [1,5].

The LHA is based on the latent heat of melting and solidification of a phase change material (PCM). Different PCM choices and applications have been reviewed elsewhere, e.g. [6]. The benefits of LHA over sensible heat storage are a more compact design and lower thermal mass, i.e. sensible heat, at critical temperatures below 20 °C.

The TES technology is better suited for gasoline engines where excess heat to charge the TES is readily available. However, automotive TES has not become commercial success due to the extra space needed for the accumulator.

The thermal efficiency of modern automotive diesel engines is so good that excess heat in the coolant loop to charge a TES is hardly available at subzero outdoor temperatures. The situation becomes even more severe in mail delivery operation where the average driving speed is low and the drive cycle includes plenty of idling. The engine may even need additional heating to maintain a desired operation temperature of above 70 °C. If a diesel powered additional heater like Webasto or Ebersprecher is used this may ruin the fuel economy of van, e.g. Itella Ltd has recorded an increase in fuel consumption from 9 l/ 100 km in the summer to 12 l/ 100 km in the winter for a VW Caddy 1.9 TDI in mail delivery operation [7]. This increase is mainly attributed to the additional heater.

One option to charge a TES would be the use the excess heat of the exhaust gases by using a gas to liquid heat exchanger in the tail pipe. Such an exhaust gas heat recovery system (EGHR) has previously been proposed for interior heating [8,9] and temperature optimisation of a hybrid electric vehicle [10].

In this study, a combination of EGHR and LHA was built in VW Caddy 1.9 TDI of Itella Ltd and tested on a laboratory dynamometer using a simulated drive cycle and in real mail delivery operation in the city of Oulu (65 °N), Finland in February 2009. The outdoor temperature varied between 0 and – 20 °C during the test period.

2. Experimental

2.1. The test vehicle

The test vehicle was a VW Caddy 1.9 TDI of Itella Ltd, Figure 1, equipped with a diesel fuelled Webasto Thermo Top V additional heater (AH). The engine was turbocharged high pressure unit injector type.

The thermostat settings for the radiator to start cooling the coolant and for the AH to start heating the coolant were 82 and 70 °C, respectively.

2.2. The system studied

The system studied is presented in Figure 2. The exhaust gas heat recovery system (EGHR) and the latent heat accumulator (LHA) were connected to the interior heater loop without any active thermostat control. The hot coolant from the EGHR was both charging the LHA and giving additional heat to the engine. An electric pump was added to the loop to assist the engine water pump.

The diesel fuelled additional heater (AH) was either connected to or disconnected from the system. The temperature measurement points are also shown in Figure 2 and listed in Table 1.

2.3. Design of the latent heat accumulator

The desired PCM melting point was between the thermostat setting of 70 and 82 °C. Stabilised trisodium phosphate dodecahydrate (Climsel C70 by Climator A/S, Sweden [11]) melting at 75 °C was selected as the PCM for the heat accumulator for it has high latent heat of fusion (280 kJ/kg) and high density (1,7 kg/dm^3). 4 kg of the salt was packed into stainless steel tubes for a typical shell and tube configuration [1,5] and tubes were then installed in a commercial 6 dm^3 vacuum insulated stainless steel wide mouth dewar flask (Statebourne OD6), Figure 3. The LHA specifications are given in Table 2 and the theoretical energy content with 83 °C temperature difference in Table 3 respectively. The total heat content of the LHA was 2500 kJ (=700 Wh), of which the latent heat of the PCM salt accounted for 45 %.

The hot coolant from the EGHR was fed to the bottom of the dewar flask using the central pipe shown in Figure 3, flowing upwards between the PCM filled tubes and returned through a connector in the top cover of the flask. The LHA was installed into the top part of the engine compartment of the van, Figure 4.

2.4. Design of the exhaust gas heat recovery system

Several commercial and self made gas to liquid heat exchangers were tested as the EGHR. An aluminium lamella heat exchanger (Mocal 190×170) typically used for engine oil cooling showed good heat recovery efficiency and low exhaust gas pressure drop. Two heat exchangers were packed into a steel jacket in series in a counter flow arrangement, i.e. the coolant flow was opposite to the exhaust gas flow, and assembled in the front part of the tailpipe, Figure 5.

2.5. Dynamometer testing

The dynamometer testing was performed at – 10 °C outdoor temperature using a simulated drive cycle, Figure 6. In addition to the temperatures shown in Figure 2 the exhaust gas emission from the engine were recorded using constant volume sampling (CVS) exhaust gas tunnel and AMA 3000 gas analyzers.

The test matrix is given in Table 4. The performance of the additional heater was compared with the combination of EGHR an LHA. During the EGHR/LHA measurements the AH was disconnected. The LHA was either fully charged or discharged before the measurement. The measurements with the LHA discharged were used to study the possible negative effects of the additional thermal mass of the discharged LHA.

Neither the fuel consumption nor the exhaust gas emissions of the additional heater were recorded.

2.6. Field testing

The field testing was performed in real mail delivery operation in the city of Oulu (65 °N), Finland. The testing of the original van without the EGHR and LHA took place in January 2007 and the modified van with the EGHR and LHA for two weeks in February 2009, Figure 1. During the first week in 2009 the AH was connected to study the effects of EGHR and LHA to the AH run time. During the second week the AH was disconnected to study how the van would perform without the AH.

The outdoor temperature varied between 0 and – 20 °C during the field testing.

Neither the driving speed nor the fuel consumption could be recorded during the field testing. However, the average speed was below 50 km/h. In addition, the performance of the modified van was tested on 600 km highway driving from Oulu to Helsinki at 0 °C outdoor temperature to study the possible overheating of the engine.

3. Results

3.1. Laboratory testing of the latent heat accumulator

The performance of the latent heat accumulator was verified in a laboratory test bench using hot (+ 93 °C) and cold (+ 10 °C) coolant (water/glycol mixture) to charge and discharge the LHA respectively. The coolant flow rate was varied between 3 to 6 l/min and the discharge time between 30 and 60 min. The charge time was 60 min. The cumulative energy in 11 charge/discharge cycles is close to the theoretical value of 2500 kJ as shown in Figure 7. It typically took 45 min to charge the LHA and below 15 min to discharge it. High peak powers between 10 and 15 kW were recorded for the first minute of discharge then the hot liquid coolant was removed from the LHA.

3.2. Dynamometer testing

The simulated drive cycle on the dynamometer included 20 min of accelerations to 15 to 50 km/h followed by short stops for simulated mail delivery followed by acceleration to 120 km/h simulating highway driving, Figure 9. In the standard configuration with AH but without EGHR and LHA it took 200 s for the coolant to reach 20 °C, Figure 8. When a fully charged LHA was used, it took only 20 s to reach 20 °C. When the LHA was empty, only EGHR was speeding up the heating of the engine and it took 300 s to reach the 20 °C.

This heating up period is critical for CO, HC and NOx emission of the engine, as shown in Figure 9. The CO and HC emissions were reduced by 84 % and NOx emissions by 53 % due to the faster response of the fully charged LHA and EGHR in comparison to AH only. When an empty LHA was in the system the CO and HC emissions were slightly increased (13-27 %) and NOx emission decreased, but this change was within the experimental error of ± 10 %. As the response of the AH is too slow for efficient emission control, it should be switched on several minutes before the cold start, e.g. by using a timer.

After 400 s of driving the temperature of the engine (or coolant) of the standard system with the additional heater reached that of the fully charged LHA system and thereafter remained higher. The higher operation temperature of the standard system is shown as a lower CO2 emission and theoretical fuel consumption in comparison to the experimental system with fully charge LHA and EGHR during the first 20 min of driving, Figure 10. As, the distance passed during these 20 min was 5,5 km, the fuel consumptions of the standard system and the experimental system with fully charged LHA were 0,46 dm^3 and 0,49 dm^3 respectively. However, if the estimated fuel consumption of 1 dm^3/h (= 0,33 dm^3 in 20 min) of the additional heater is calculated, the total fuel consumption of the standard system of 0,79 dm^3 exceed even that of the experimental system with a discharged LHA comprising 0,55 dm^3.

3.3. Field testing

Reference values for the original van were recorded in January 2008. Typical temperature profiles for one day drive cycle are shown in Figure 11. The AH was operating for about 1 h in the morning and 0,5 h after the lunch brake. The outdoor temperature was about – 10 °C.

The modified van was tested in February 2009. The temperatures of one day drive cycle during the first week when the additional heater was connected together with the EGHR and LHA are shown in Figure 12. In this case, the AH was only operating for 25 min during the start up and it took 15 min for the coolant to reach 70 °C. The outdoor temperature varied between – 6 and – 10 °C. This is an indication that the use of the EGHR would reduce the run time of the AH which would only be needed for the cold start. The results in Figures 11 and 12 are not directly comparable for the drive cycles were different.

The temperatures of one day drive cycle after the AH was disconnected are shown in figure 13. The LHA and EGHR were heating up the coolant to 70 °C in 30 min and the EGHR was sufficient to maintain the desired coolant temperature for the rest of the drive cycle. The outdoor temperature was varying between – 14 °C in the morning and – 5 °C in the afternoon. This is an indication that a combination of EGHR and LHA could replace a diesel fuelled AH in cold climates down to temperature of – 15 °C.

There was no overheating of the engine during the 600 km highway driving at 0 °C. The possible overheating could be avoided by a thermostat controlled bypass of the EGHR as proposed in [8].

4. Conclusions

We have shown that a simple exhaust gas heat recovery system helps to maintain the temperature of a modern automotive diesel engine at a desired range of > 70 °C in cold climates with subzero temperatures. Combination of the EGHR with thermal energy storage, e.g. a latent heat accumulator, could replace a diesel fuelled additional heater typically used for temperature optimisation of diesel engines in cold climates.

The response of the LHA is faster than that of the diesel fuelled AH and the cold start emissions are greatly reduced if the AH is not started several minutes before the engine start.

The true benefits of the proposed system for fuel economy and emission reduction should be evaluated by measuring the total fuel economy and emissions of the vehicle including the engine and the additional heater and by considering the additional weight of the LHA and EGHR.

Acknowledgements

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Abbreviations

AH	diesel fuelled additional heater (Webasto)
EGHR	exhaust gas heat recovery system
LHA	latent heat accumulator
PCM	phase change material
TES	thermal energy storage

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Figure captions

Figure 1. VW Caddy 1.9 TDI of Itella Ltd during test driving in the city of Oulu.

Figure 2. The system studied.

Figure 3. The LHA tube heat exchanger and dewar flask.

Figure 4. The latent heat accumulator installed in the VW Caddy.

Figure 5. The EGHR installed in the VW Caddy.

Figure 6. The VW Caddy on the test dynamometer.

Figure 7. Cumulative energy of the LHA prototype in the laboratory test bench during 11 charge/discharge cycles. Every second peak is for charge and every second for discharge.

Figure 8. The driving speed of the simulated drive cycle and coolant temperatures during the dynamometer testing at – 10 °C outdoor temperature.

Figure 9. CO, HC and NOx emissions during the first 20 min of the dynamometer testing.

Figure 10. a. CO2 emissions during the first 20 min of the dynamometer testing, b. theoretical fuel consumption.

Figure 11. Temperature profiles during one day mail delivery operation of the original van.

Figure 12. Temperature profiles of the modified van with the additional heater connected.

Figure 13. Temperature profiles of the modified van with the additional heater disconnected.

Tables

Table 1. Temperature measurement points.

Table 2. Latent heat accumulator specifications.

Table 3. Theoretical heat content of the LHA with a temperature difference of 83 °C.

Table 4. Test matrix for the dynamometer testing at – 10 °C.

Figure 1.

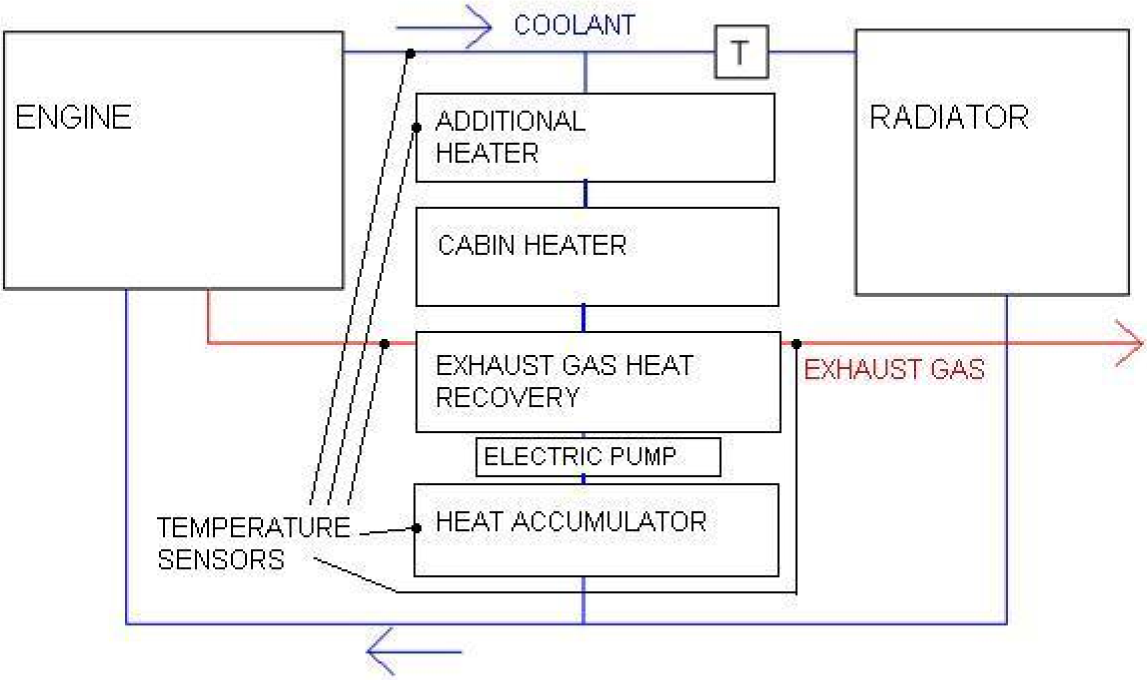

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

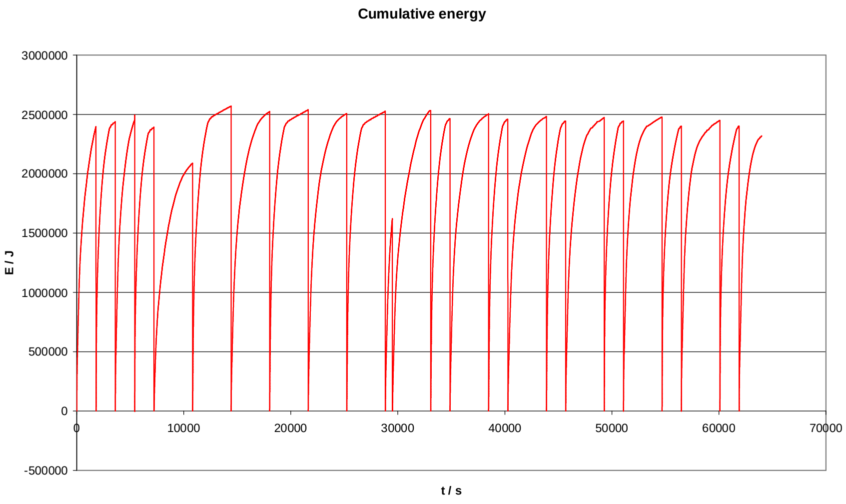

Figure 7.

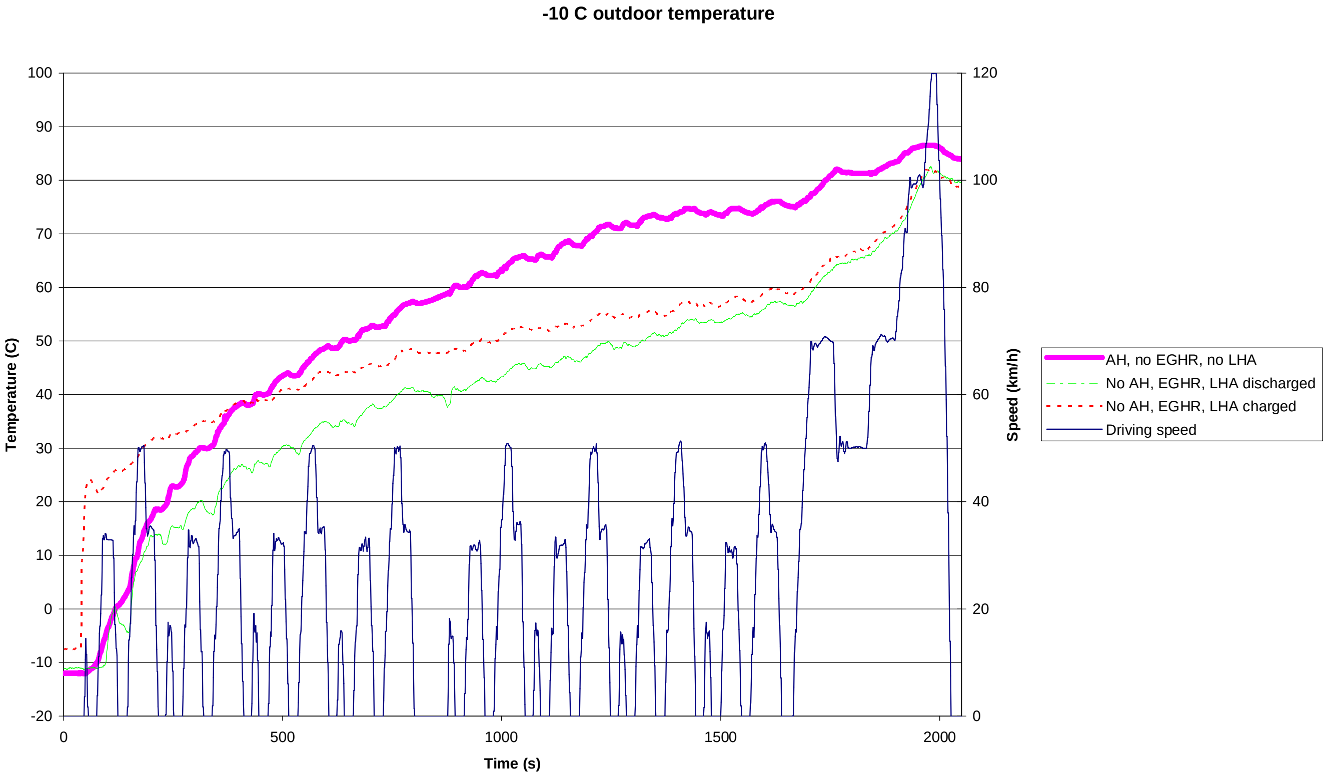

Figure 8.

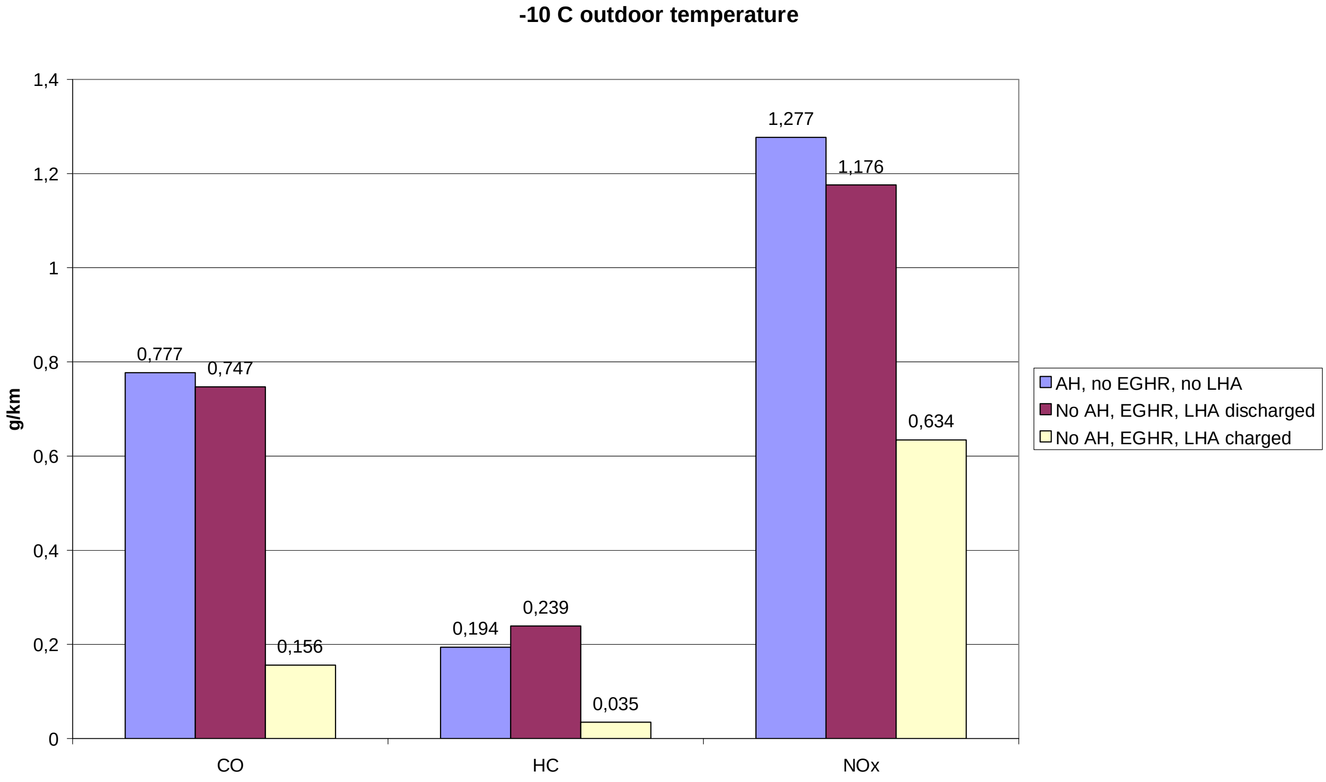

Figure 9.

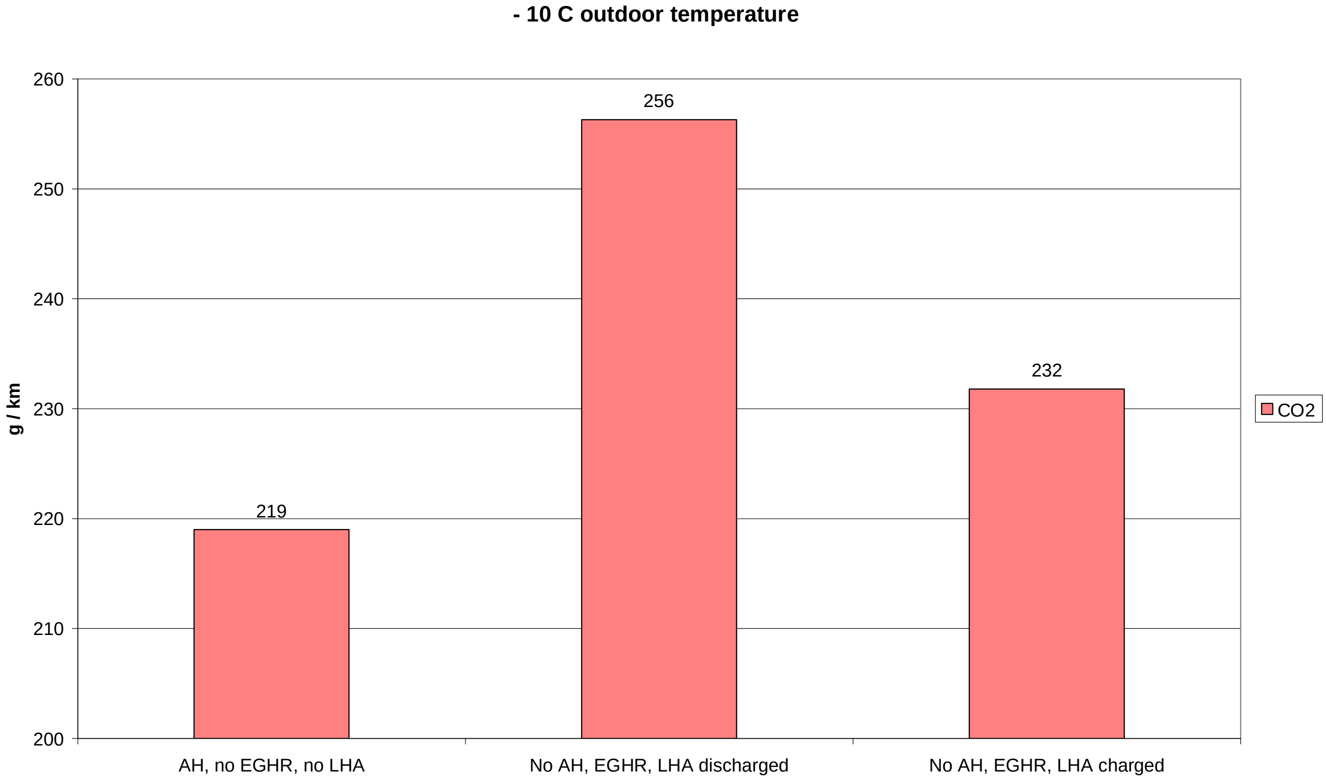

Figure 10 a

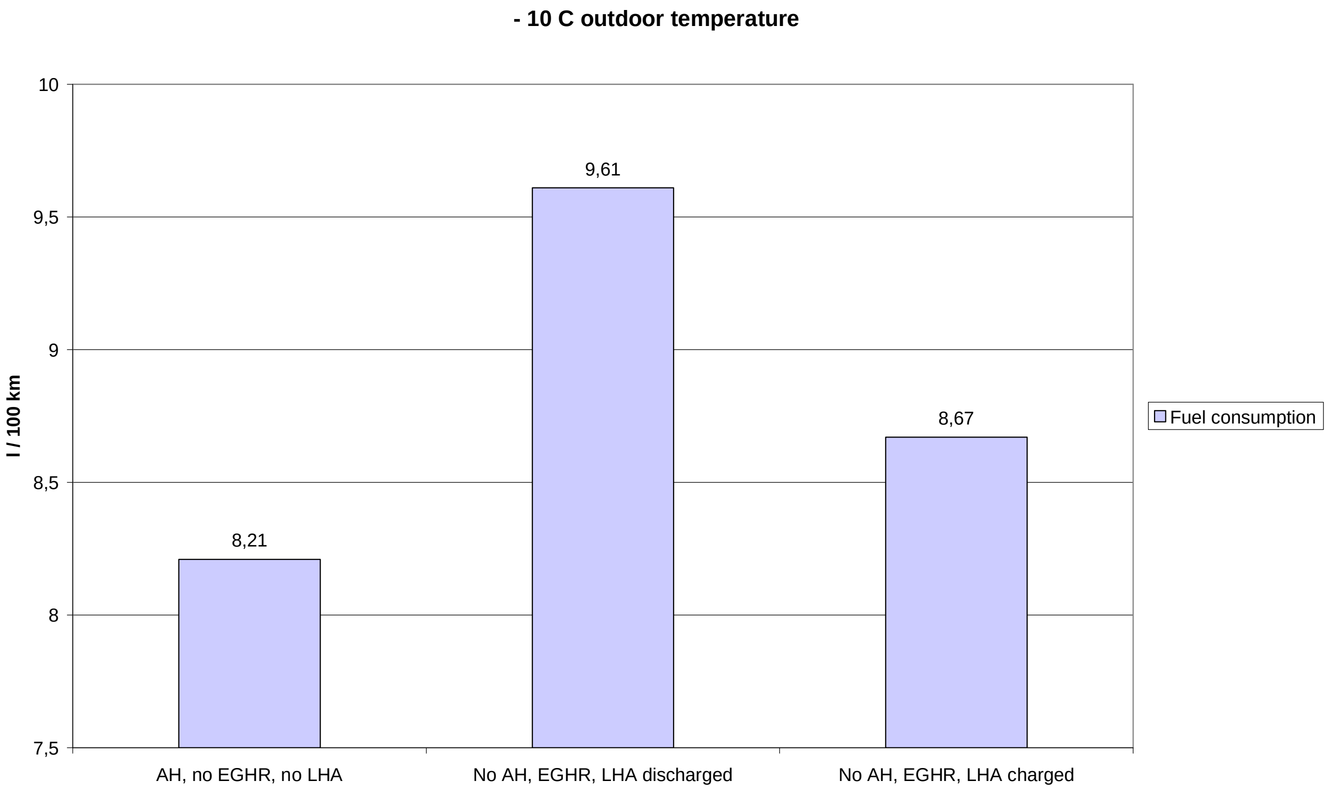

Figure 10 b.

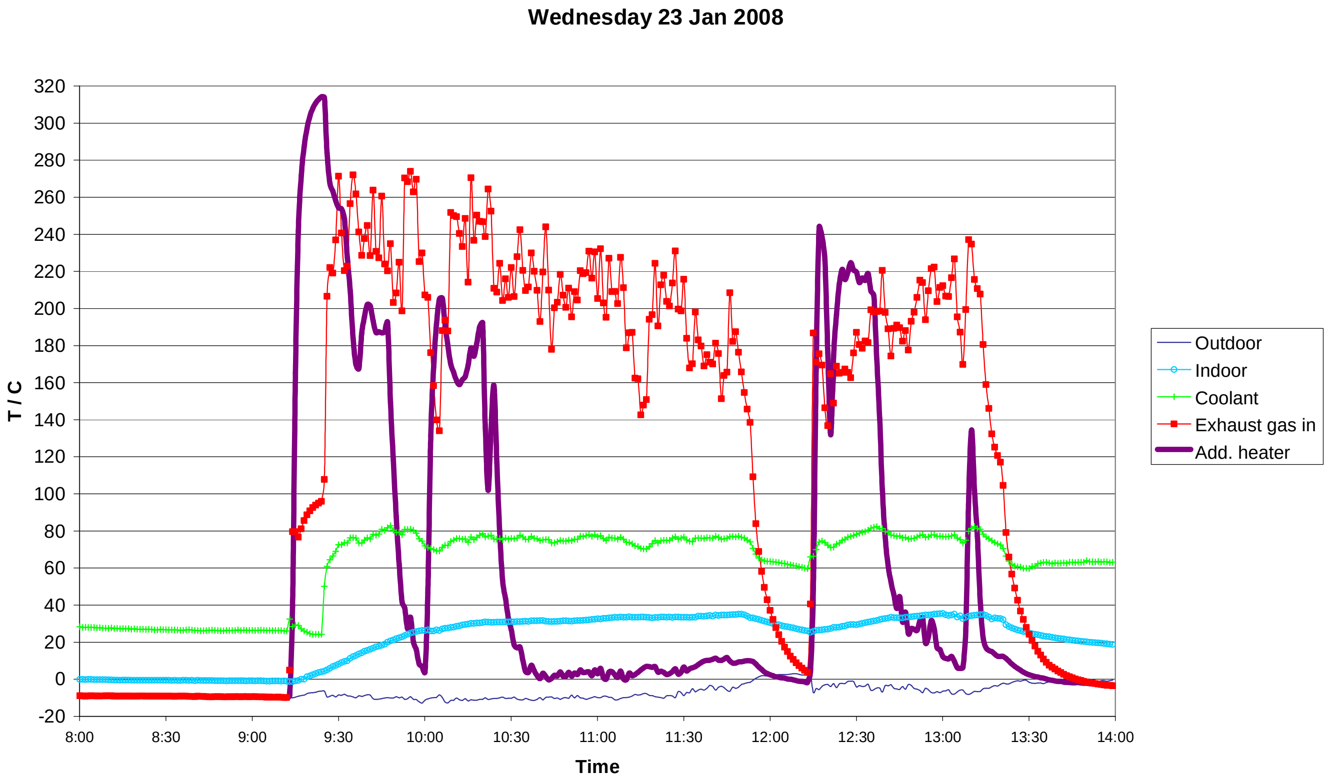

Figure 11.

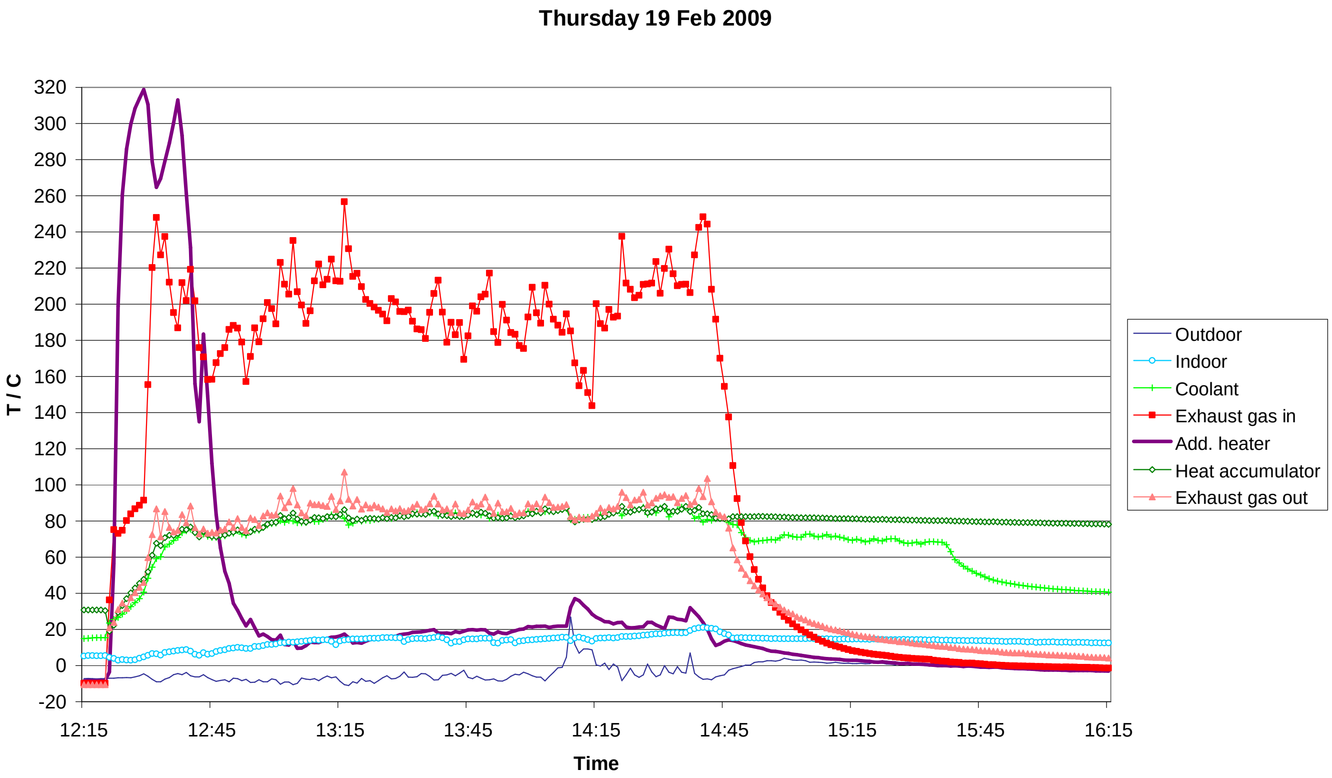

Figure 12.

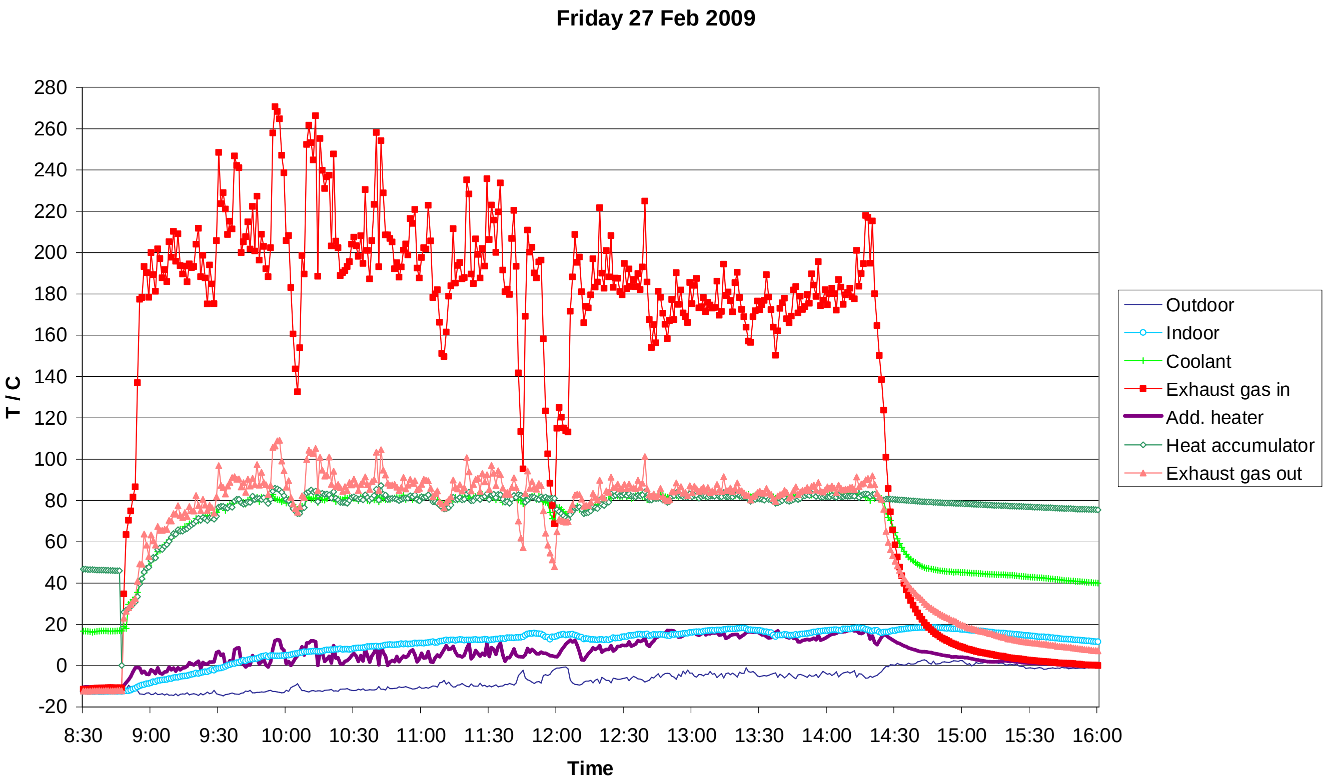

Figure 13.

Table 1.

Temperature sensors
In the PCM heat accumulator
In the coolant after the engine
In the exhaust gas before heat recovery
In the exhaust gas after heat recovery
Exhaust gas of the additional heater
Outdoor temperature
Indoor driver cabin temperature

Table 2.

	Pieces	**Mass**	**Volume**	**Height**	**Inner diameter**	**Outer diameter**
		g	**dm^3**	**mm**	**mm**	**mm**
Dewar, Statebourne OD6	1	3200	6,08	300	185	195
Stainless steal pipes	36	5256 (=36*146)	4,01 (=36*0,11)	220	23	25
PCM, Climsel C70	*36*	*4032 (=36*112)*	*2,49 (=36*0,07)*			
Coolant	1	2200	2,07			

Table 3.

	Mass	**Heat content**	**Latent / sensible heat**
	g	**Wh**	
PCM salt	4032	314	Latent
		139	Sensible
Stainless steal pipes with end caps	5285	61	Sensible
Coolant	2200	167	Sensible
Inner surface of the dewar	1500	17	Sensible
Total	**13017**	**698**	

Table 4.

Experiment	Additional heater	EGHR	LHA
1.	Connected	Disconnected	Disconnected
2.	Disconnected	Connected	Fully charged
3.	Disconnected	Connected	Discharged