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ENGINE PRE-WARMING HEAT STORAGE SYSTEMS AS SOLUTIONS TO COLD-STARTING PROBLEMS OF DIESEL ENGINES

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Abstract

The system described in this article provides a solution to the cold-starting problems of Diesel engines by recycling the waste heat of the vehicle produced during operation. The heat regained from exhaust gases and/or from the coolant is stored in a heat storage system connected to the cooling system. The pre-warming taking place a few minutes prior to starting is also realised through the cooling system by applying a battery-fed water pump.

The mass and the volume of the heat storage installation is limited, thus in order to attain the adequate heat capacity a storage material of high energy density is needed. It has been shown during the theoretical examination of systems with phase-changing storage materials that the traditional heat storage construction does not let the phase changing end in a few minutes, thus only a part of the stored latent heat can be regained.

Rapid pre-warming can be attained by using an experimental installation of the sensible heat storage system containing a mixture of water and glycol, mounted in an Ikarus bus and by applying intensive circulation, which results in an efficient way of utilising the stored heat. It is mainly at the pistons that the rapid pre-warming of the engine leads to an increase of temperature. As a consequence, the friction at the pistons decreases and the starting of the engine requires less starting power. The higher temperature of the cylinder walls is also more favourable for burning and the end temperature of compression needed for self ignition is more easily attained. During the experiments in the cold wind tunnel, the Diesel engine started firmly every time after the pre-warming procedure of the heat storage system had taken place.

Keywords: Diesel engine, cold-starting, heat storage, engine pre-warming.

1. Introduction

Increasing energy prices call for the recycling of waste energy. A considerable amount of such energy is produced in internal combustion engines of vehicles. Only one third of the energy of the fuel is turned into mechanical work, the rest is spread into the environment through exhaust gases and through the cooling system of the engine in the form of waste heat. Although warm coolant is used for heating the passenger's compartment, unused heat is still significant even in winter. On the other hand, the starting problems at Diesel engines can be greatly reduced or given a solution to if there is enough heat at disposal.

Diesel engines at $-10°$C can cool down to such an extent that the power needed to start the engine will be several times higher than that for a warm engine, which is basically due to increased friction forces at low temperature [1]. On the other hand, the capacity of the cold battery decreases, thus the power at disposal, too [2]. To such starting problems there have been several technical solutions.

The cold starting system described in this article presents a solution by using the waste heat produced while the engine of the vehicle is running. The time difference in the functions of heat supply and demand calls for the use of a heat storage system.

The waste heat of the exhaust gases or of the coolant is stored in an isolated heat storage installation and most of it is preserved for long after the engine has stopped running.

The energy stored can be used for pre-warming the Diesel engine prior to the first attempt to start it resulting in favourable conditions for starting even at low temperatures.

2. Scheme of Engine Pre-Warming Systems Using Waste Heat

2.1. Theoretic Scheme of the Heat Storage System

Fig. 1 shows some possible connections of the engine and the heat storage system in engine pre-warming systems using engine waste heat.

In systems 'A' and 'B' the heat storage installation is in thermal connection with the exhaust gases and the cooling system of the engine, and in the first place it stores the thermal energy of the exhaust gases. In the system designated with 'C' the heat storage installation is connected exclusively to the cooling system of the engine and it stores the thermal energy regained from the hot coolant.

In all the three systems engine pre-warming prior to starting can be realised by circulating coolant of the engine. In a direct or indirect way the regained heat warms up the circulated coolant, which results in an increase of temperature mostly at the pistons, thus reducing friction at the most critical places. An additional positive result of a higher cylinder wall temperature is the easier attaining of the end temperature of compression needed for self-ignition.

For version 'A' the temperature of heat storage is higher than 100°C. A heat transport cycle must be installed between the heat storage installation and the cooling system of the engine. During heat storage, the exhaust gases

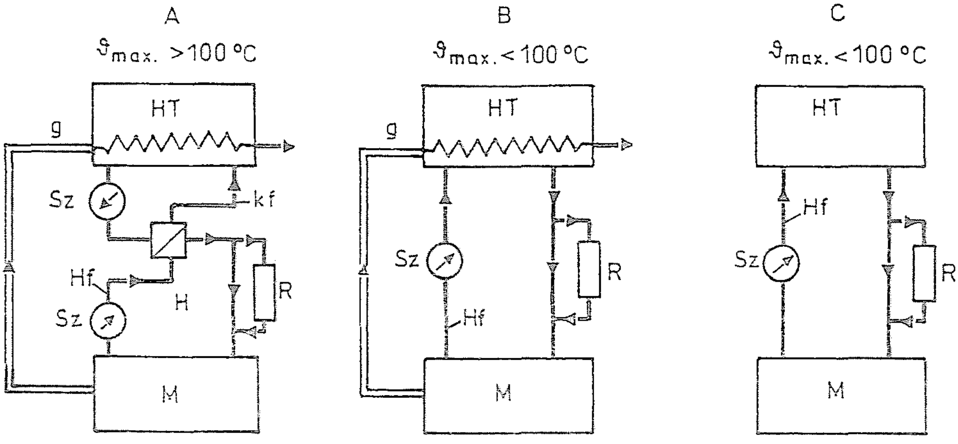

Fig. 1. Engine pre-warming systems with heat storage. HT – heat storage unit, Sz – pump, M – engine, Hf – coolant, H – heat exchange, kf – heat transport fluid, g – exhaust gas, R – radiator, fuel filter heating, ϑ_{max} – maximum temperature of the heat exchanger unit

pass through the heat exchanging surface of the heat storage installation and pass on a part of their thermal energy to the heat storage material. During heat regaining, i.e. prior to starting the engine, the pumps mounted in the cooling system of the engine and fed by the battery start circulating both the coolant and the heat transport fluid. The heat stored in the heat storage system reaches the engine by getting through the heat exchanger and then the cooling system of the engine.

For systems 'B' and 'C' the temperature of heat storage is below 100°C and therefore the heat storage installation can be mounted directly in the cooling system of the engine. Consequently, only the battery-fed coolant pump has to be started for the pre-warming procedure of the engine.

Moreover, fuel supply problems of the fuel supply system at low temperatures can be avoided by using the thermal energy of the heat storage system, i.e. the hot coolant – for example by the pre-warming of the fuel filter.

In systems 'A' and 'B' the energy regained from the exhaust gases can also be used for heating of the running vehicle by continuously cooling down the exhaust gases.

2.2. *Criteria for Choosing the Heat Storage Construction and the Heat Storage Material*

Multiple criteria must be regarded at the construction of a heat storage system to be mounted in a vehicle. The weight of the heat storage installation should not exceed 1 – 2% of the total weight of the vehicle in order not to decrease considerably the useful weight. The shape and volume of the heat storage installation are determined by the free space available. When developing the surface of the heat exchanger of the heat storage system it must be taken into consideration that usually a relatively long time is available for charging, since it occurs during the running of the vehicle while the process of heat regaining, i.e. warming up of the engine must be fast, lasting a few minutes.

It is suitable to use materials of high energy density for heat storage materials ensuring the highest storage capacity coupled with limited mass and volume.

One way of storing thermal energy is sensible heat storage. Here, the temperature of the storing material increases, and the heat stored per unit mass depends on the specific heat of the material and on the change of temperature.

Another way of storing thermal energy is latent heat storage. Here, the phase of the storing material is changed and heat is stored at a constant temperature namely at the phase-changing temperature. During heat addition, when changing from solid to fluid occurs, the heat storage media absorbs the melting heat while during heat extraction leading to the solidification of the heat storage medium the very same heat can be regained [3].

Both sensible and latent heat storage systems are appropriate for our purpose.

Latent heat storage materials with melting temperatures between 140°C and 200°C such as nitrates, chlorides and hydroxides must be applied in version 'A' [4]. The heat storage material can also be a heat-resistant oil. It can also be applied at sensible systems.

Phase changing materials with melting temperatures lower than 100°C, such as paraffin, fatty acids and salt hydrates must be applied in version 'B'. At sensible heat storage systems it is advisory to use an anti-freeze coolant of the engine (a mixture of glycol and water) as heat storage material. When choosing the latent heat storage material for systems 'A' and 'B' it must be taken into consideration that the temperature of exhaust gases can reach as high as 500 to 600°C. A considerable number of latent heat storage materials become chemically unstable at that temperature. Because of their probable decomposition they cannot be used here.

In version 'C' the heat storage installation and the exhaust gases are in no connection with each other, thus the temperature of the storage installation cannot exceed the maximum temperature of the coolant. It is suitable to use the coolant of the engine as a sensible heat storage material. In order to ensure the proper melting of the heat storage material we need to have a material with a phase-changing temperature at least 5 to 10°C lower than the temperature of the coolant of the running engine.

2.3. Theoretical Examination of the Pre-Warming System Using a Latent Heat Storage Installation

Theoretical examinations were based on the data of the IKARUS 400 bus. Different combinations of the heat exchanger/heat storage system and the heat storage material were used in systems 'A' and 'B' within the available volume of 0.4 m^3. The latent heat storage material was contained in tubes with double walls arranged in a ring-like form, where one of the surfaces was used for the heat exchange with the exhaust gases and the other one was used for the heat exchange with the heat absorbent fluid.

Using a mathematical model the optimum dimensions of the heat storage installation, the best heat storage construction and thermal parameters were determined for each system. An approximate mathematical model describing the instationary thermal behaviour of the system was used for the comparison of the different versions. It comprised the analysis of heat storage and heat regaining (engine pre-warming) processes in function of time [5].

In the process of engine pre-warming, all the heat extracted from the heat storage installation was presumed to reach the engine through the heat transport system. It was also presumed that warm components depending on their temperature may give off heat to the environment.

The thermal process is described by the following inhomogeneous first order differential equation:

$$(mc)_m \frac{\mathrm{d}\vartheta_m}{\mathrm{d}t} + \vartheta_m \left[R_r + (kA)_k\right] = R_r \cdot \vartheta_{fv} + (kA)_k \cdot \vartheta_k,$$

of which the particular solution satisfying the given initial conditions will give the calculated value of the instantaneous average engine temperature:

$$\vartheta_m = \frac{R_r \cdot \vartheta_{fv} + (kA)_k \cdot \vartheta_k + R_r \left(\vartheta_k - \vartheta_{fv}\right) \exp\left[-\frac{R_r + (kA)_k \cdot \vartheta_k}{(mc)_m} \cdot t\right]}{R_r + (kA)_k}.$$

Some of the results of the theoretical examinations are shown in *Fig. 2.* The characteristics of the two latent heat storage systems are found in *Table 1.* Engine pre-warming was realised by matching the optimum heat storage – heat exchanger installation geometry and the heat storage material suitable for the given purpose. This figure shows the changes in temperature in function of time for those engine parts that are in contact with the coolant, and the changes in function of time in the temperature (ϑ_{v1}) of the coolant entering the engine and in the temperature (ϑ_{v2}) of the coolant leaving the engine. For versions 'A' and 'B' the thermic data of phase-changing materials with phase-changing temperatures of 170°C and 95°C were considered, respectively.

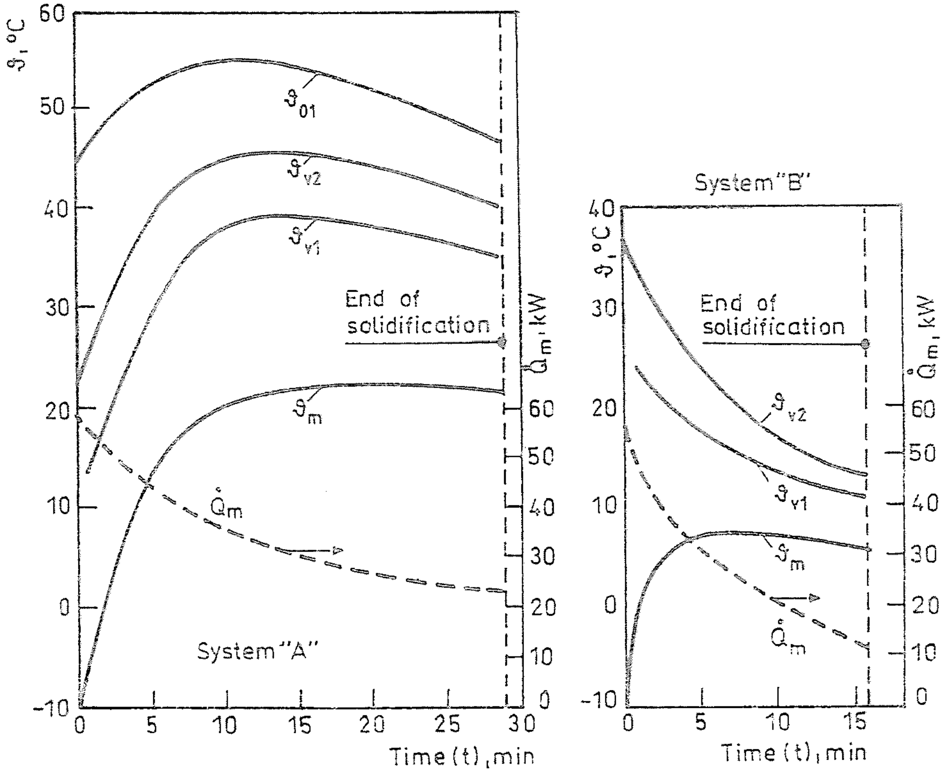

Fig. 2. Calculated values of the engine pre-warming process of an Ikarus bus realized with a latent heat storage installation. $\vartheta_k = -10°C$, $\dot{m} = 1.4$ k/s

Examinations showed that the major part of the increase in the engine temperature occurred during the first quarter of the time needed for the total solidification of the heat storage material. The reason for that is that the thickness of the solidified layer inside the heat storage installation increases continuously resulting in an increased heat resistance. That can also be

Table 1. Characteristics of latent heat storage systems

	Heat storage material	ϑ_{fv} °C	Total phase-changing heat	Total mass
System 'A'	KOH-NAOH	170	60MJ	560 kg
System 'B'	α-Naphthol	95	24.5 MJ	450 kg

deduced from the decrease of the heat per unit time $\dot{Q}_m$ used for the pre-warming of the engine.

From the second half of the time needed for total solidification on, the engine temperature remains practically constant. It even decreased to a small extent due to the heat leaving the hot parts for the environment. The solidification would not terminate during the reasonably given maximum pre-warming time of 10 minutes and therefore only a part of the stored latent heat would be used for the pre-warming of the engine, the rest of it remaining in the storage installation.

Having compared system types 'A' and 'B' we know that type 'B' is more dynamic. When starting the warming up process for system 'B' temperature increased faster since the installed heat transport cycle filled up with oil slowed down the process.

The engine pre-warming process of system 'B' realised with a sensible heat storage installation containing an anti-freeze coolant has also been investigated. Analyses showed that for the given volume only a storage instrument with a smaller heat capacity could be realised, however, all of the stored heat could be regained and used for engine pre-warming during the time of pre-warming.

3. Operational Tests on a Sensible Engine Pre-Warming System

The tests were carried out on a sensible storage system built in a bus, a Ikarus 405 vehicle for urban public transport use equipped with a Rába D.12 engine with an output of 170 kW. The mounting dimension of the installation, heat insulation included, was 0.4 m^3. The coolant used is a mixture of water and glycol.

3.1. Description of the Testing System

Fig. 3 shows the scheme of the system. Due to the directional valves (3) during the charge, i.e. the warming-up of the heat storage installation (1) exhaust gases flew through the heat storage installation instead of the silencer (4) and warmed up the anti-freeze fluid inside the storage installation.

Heat introduction was controlled by the thermostat (8) sensing the temperature of the material in the storage installation and stopping the gas flow when the maximum temperature had been attained.

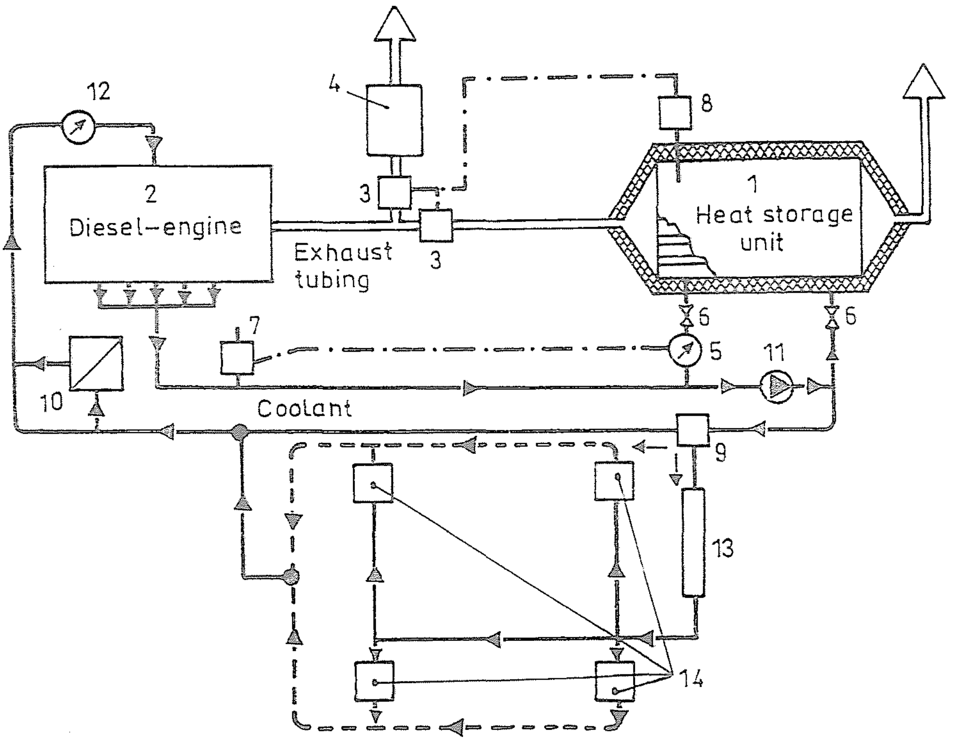

Fig. 3. Scheme of 'B'-type sensible heat storage cold-starting system mounted in an Ikarus bus. 1 – heat storage unit, mounting dimensions: 1300×775×370 mm; total mass: 250 kg; heat storage material: anti-freeze, 155 l; heat exchanger surface: 2.52 m^2; 2 – Diesel engine, type D12U Rába; 3 – directional gas valves; 4 – silencer; 5 – battery-fed water pump; 6 – shutoff valves; 7 – thermostat operating the water pump; 8 – thermostat controlling the gas valves; 9 – directional valve; 10 – fuel filter heating; 11 – check valve; 12 – water pump of the Diesel engine; 13 – sleet chaser; 14 – heaters in passenger's compartment

During engine pre-warming the hot fluid in the heat storage installation was moved by a battery-fed pump (5) towards the fuel filter (10) and the engine (2), thus warming them up.

When the vehicle was running and heating was required the coolant passed through the sleet-chaser installation (13) and the heater (14). If the temperature of the coolant coming from the engine was less than the value set for the thermostat (7), then the battery-fed pump (5) started operating and additional heating performance could be extracted from the heat storage installation.

When stopping the vehicle, thermic circulation could take place between the heat storage installation and the engine causing discharge of the heat storage installation. Closing of the mounted valves (6), however, prevented it from happening.

3.2. Operational Tests of the Warming-Up Process of the Heat Storage Installation

The maximum temperature, i.e. the warming-up temperature of the given heat storage installation is basically determined by the operation of the engine, since it determines the temperature and mass flow of the exhaust gases. It also affects the ambient temperature to a smaller extent through the heat loss of the heat storage installation.

The warming-up process of the heat storage installation was examined without heat extraction and with different running conditions of the vehicle. *Fig. 4* demonstrates the change in the average temperature of the heat storage installation in function of time during those experiments. The parametric conditions of the tests are shown in *Table 2.* The warming-up time, i.e. the time needed to bring the temperature from the initial heat storage temperature of 20 – 30°C to the set maximum temperature of 95°C varied between 27 and 45 minutes depending on the kind of the operation.

Table 2. Parameters of the charging of the sensible heat storage system

Measurement number	ϑ_k [°C]	Engine revolution number [1/min]	ϑ_k [°C]
1	+13	2200 – 2300	280
2	+20	1000 – 2000	190 – 300
3	+20	2300	310
4	+20	2200	300
5	+20	2200	270 – 290
6	−15	1800	270
7	+20	changing	350 – 420

When the vehicle was stationary with the engine running idle the warming-up procedure (the initial part of measurement 2) was quite slow due to the low gas temperature and the small mass flow of gases

Under real operating conditions with the vehicle moving (measurement 7) the maximum temperature of the heat storage installation was attained

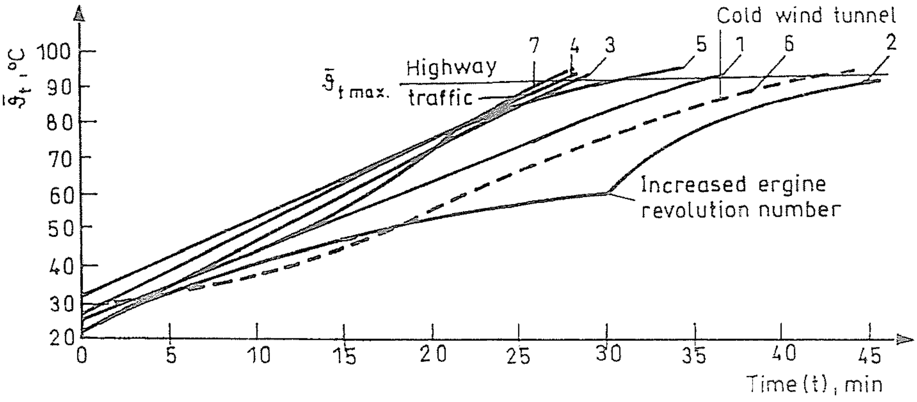

Fig. 4. Test results during charging of the sensible heat storage system mounted in the Ikarus bus. Measurements 1 – 6 with a stationary vehicle, measurement 7 in highway traffic

within half an hour. The energy level of the heat storage installation increased by approx. 42 MJ, thus out of the waste heat of the exhaust gases approx. 25 kW of thermal energy was utilised in average for the heating of the heat storage installation. Once the heat storage installation had been warmed-up, the warm coolant could be used for heating the passenger's compartment. Therefore, the heat storage installation served as a fluid-gas heat exchanger producing 25 kW of thermal energy out of the waste heat of the exhaust gases.

3.3. Examination of the Cooling Processes of the Engine and the Heat Storage Installation and Examination of the Rate of Power Input of the Starter

The cooling down of the hot engine and the warm heat storage installation was examined in a cold wind tunnel at an ambient temperature of −15°C. According to test results in *Fig. 5,* the hot engine of 72°C would cool down to 0°C in 5 and a half hours and would practically reach the ambient temperature in 9 hours (curve 1). The temperature of the engine had been defined as the average of the values measured at cylinder wall parts that are in contact with the coolant.

As the temperature of the engine decreased the starting power needed for restarting increased. Therefore, the rate of power input of the starting motor was measured at different engine temperatures. *Fig. 5* shows the

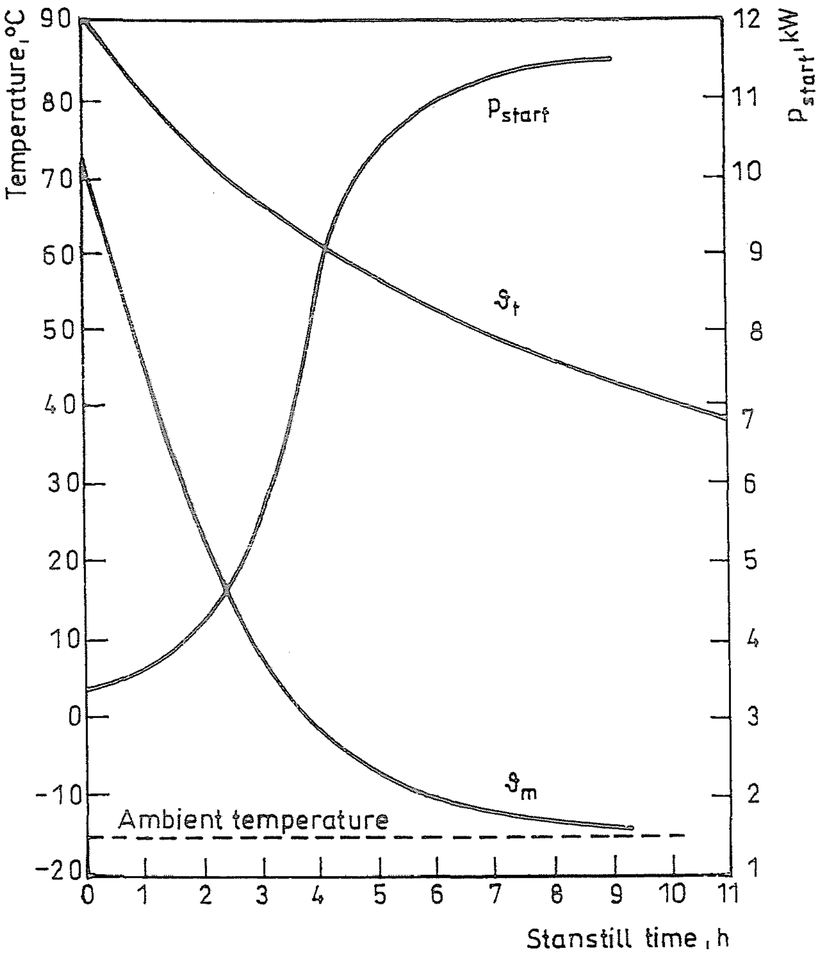

Fig. 5. Examination of the cooling of the engine and the heat storage unit in the wind tunnel. P_{start}: the power input of the starter when starting at a given engine temperature

starting power corresponding to the momentary calorific condition of the engine (curve 2). Thus 3 and a half hours after stopping the engine at −15°C the required restarting power would be doubled and in 5 to 6 hours it would be tripled. The battery feeding the starter cooled down even faster than the engine and the so-decreased capacity of the battery would only assure a relatively smaller power. All these facts may eventually lead to starting problems.

The thermal capacity of the heat storage installation, i.e. the thermal energy available for engine pre-warming would gradually decrease during standstill. For sensible heat storage systems the decrease of thermal capacity is directly proportional to the changing of the average temperature of the fluid. The speed of cooling down depends on the construction of the heat storage installation, on the quality of insulation and on the ambient temperature. *Fig. 5* shows the change of the average temperature of the experimental heat storage installation at an ambient temperature of −15°C (curve 3). During the 9-hour standstill the heat storage temperature of 91°C decreased to 40°C and consequently the thermal energy available for engine pre-warming will decrease as well. However, experiments showed that this amount of energy would still be adequate for an engine pre-warming resulting in a safe starting.

The cooling of the heat storage installation during standstill was considerably influenced by the heat escaping at the non-insulated gas-fluid heat exchanger surface. In engine pre-warming systems type 'C' the heat storage installation is not in contact with the exhaust gases, thus a heat storage construction can be developed with less heat loss.

4. Operational Tests of Engine Pre-Warming

Operational tests of engine pre-warming by using the heat of a heat storage system were carried out on a system mounted in an IKARUS IK-415 bus shown in *Fig. 3*, designated by B. The pre-warming procedure of the cold engine was carried out as described in part 3.1.

A part of the series of experiments took place at an ambient temperature of 20°C and only the Diesel engine and the parts in contact with the coolant had been cooled down prior to warming up. Another part of the series of experiments was carried out under real operational conditions in winter in a special wind tunnel where the whole vehicle was cooled down. In order to define the thermal state of the engine, temperature was measured at three places at the outer wall of the part of the crankcase in contact with the coolant and then the three was taken an average of. *Fig. 6* shows the change of the so-defined average cylinder wall temperature $\Delta\vartheta_m$ during the pre-warming experiments.

The maximum temperature change that can be attained at Diesel engines depends primarily on the amount of energy that can be extracted from the heat storage, which can be characterised by the initial temperature of the heat storage installation at sensible systems. The rate of increase of temperature or the time needed for the engine temperature to attain its maximum is most significantly determined by the intensity of the circulation of the coolant. *Fig. 6* also shows for each experiment the initial temperature of the heat storage installation and that of the engine, the ambient temperature, the intensity of the circulation of the coolant and the average

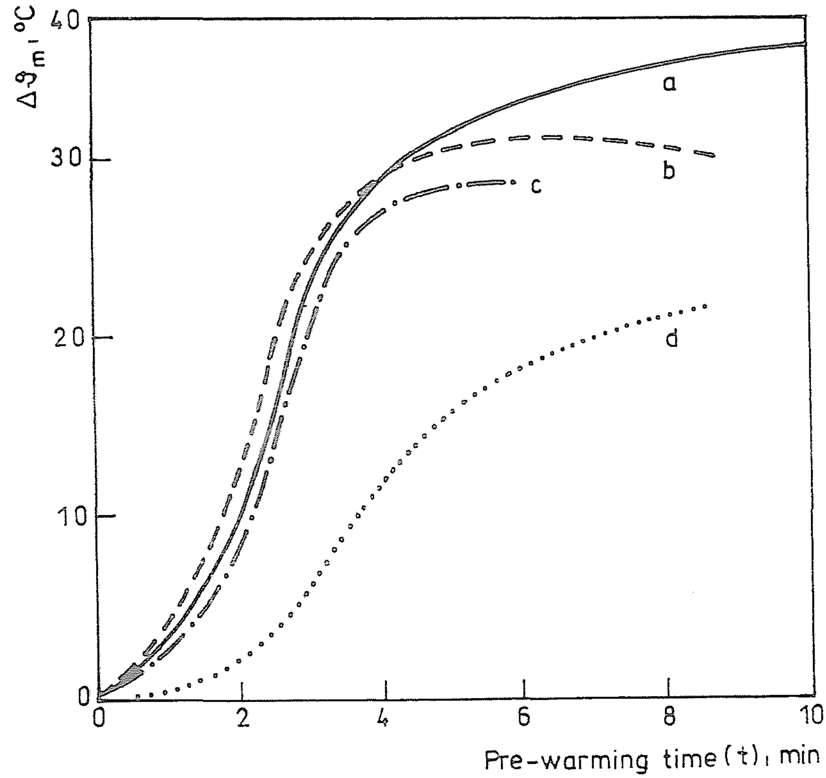

Fig. 6. Results of the tests of the engine pre-warming system mounted in the Ikarus bus. $\Delta\vartheta_m$: the change of the average cylinder wall temperature

cylinder wall temperature prior to starting. *Table 3* shows the parameters of each measurement.

A high initial temperature of the heat storage installation is favourable for engine pre-warming but the initial temperature depends on the stand-still time and the ambient temperature for each heat storage construction. Increasing the intensity of the circulation of the coolant will positively influence the utilisation of the available energy for engine pre-warming. When circulation starts the warm coolant coming from the heat storage installation primarily warms up the cylinder wall in contact with the coolant, but some part of the heat reaches the environment through non-insulated parts in contact with the coolant. Another part of the heat flows from the warmed-up parts of the cylinder to parts of the engine not in contact with the coolant.

At a more intense coolant circulation the rate of increase of the cylinder temperature is bigger and the amount of heat reaching the environment is

Table 3. Parameters of the tests of the engine pre-warming system

Symbol of the measurement	Properties of the measurements				
	ϑ_{t0} [°C]	ϑ_{m0} [°C]	ϑ_k [°C]	$\dot{m}_{ff}$ [kg/s]	Temperature of pre-warmed engine [°C]
a	70.5	−6	+20	0.583	+30
b	55.4	−5	−10	0.861	+25
c	43	−13	−15	0.805	+16
d	38	−10	−15	0.611	+11

smaller as can be seen at experiment 'b'. Due to the bigger mass flow the maximum average cylinder wall temperature is attained in 6 minutes, while the major part of the thermal energy in the heat storage installation reaches the engine and then it flows from the hot cylinder wall to other parts of the engine. At experiment 'a', in spite of an engine pre-warming with a much higher initial temperature the initial rate of increase of the temperature was not bigger, which is explained by the less intense circulation of the coolant, whereas the temperature of the wall of the cylinder increased all along the experiment due to the bigger storage capacity. At measurement 'd', when the initial low temperature of the heat storage installation was followed by an engine pre-warming process realised by a circulation of low mass flow, the rate of temperature increase was smaller than in the previous cases.

Fig. 7 shows the results of engine warming-up 'c'. The bus was kept for days in the cold wind tunnel, within which time engine pre-warming experiments took place several times. Prior to measurement 'c' the heat storage installation had been warmed up with the exhaust gases of the Diesel engine. It was followed by a standstill period of 9 hours at −15°C and consequently by the next engine pre-warming experiment. The figure shows the change in the temperature ϑ_1 of the coolant flowing to the engine, the change in the temperature ϑ_2 of the coolant leaving the engine and the changes in the temperatures ϑ_m measured at different points of the cylinder wall. The momentary heating performance used for engine pre-warming can also be seen in the diagram: for a short time a very huge amount of heating performance with a peak of 120 to 125 kW can be obtained from the heat storage system resulting in fast warming-up.

Attempts at starting the cold engine kept in the cold wind tunnel failed. Following a few minutes of engine pre-warming using the heat stored in the heat storage installation the Diesel engine started easily, each time. The fuel filter was also warmed up to 20°C and was then kept constantly at this temperature while the engine was running. As a result, no paraffin separation occurred that could have caused blocking up of the cold fuel filter thus fuel supply problems leading to stalling.

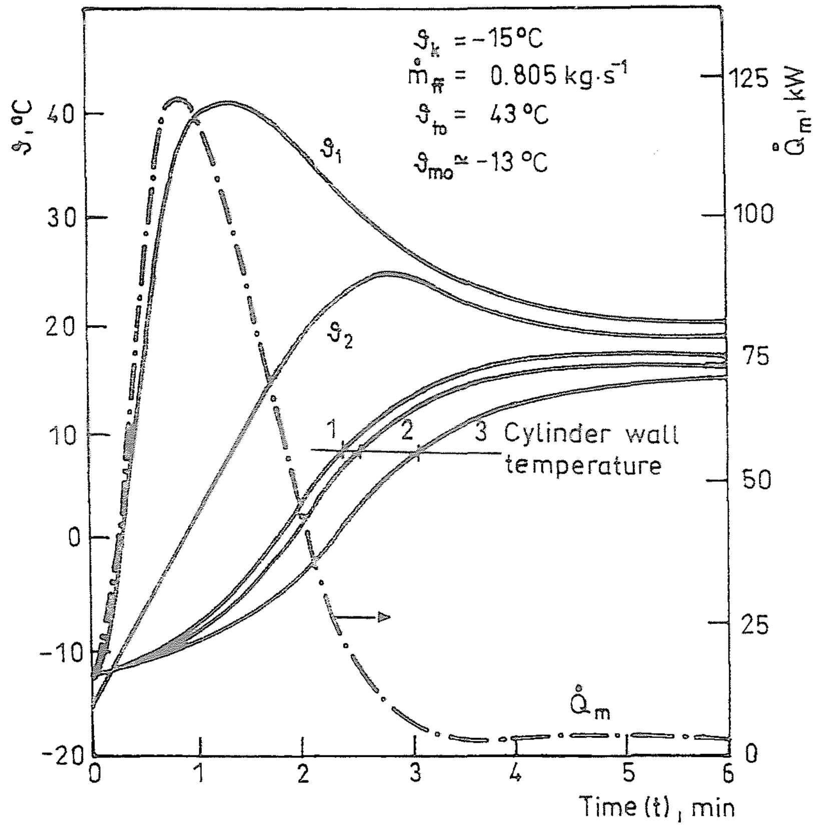

Fig. 7. Engine pre-warming test in the cold wind tunnel. 1,2,3: temperatures measured at different parts of the cylinder wall; Q_m: the momentary heating performance used for engine pre-warming

5. Conclusions

It has been found in the tests that it is the most suitable to mount the heat storage installation used for the pre-warming of Diesel engines directly in the cooling cycle of the engine. Rapid pre-warming and good utilisation of the heat stored can be achieved if the heat storage material and the coolant are identical and if there is an intense fluid circulation during pre-warming.

Since the biggest increase in temperature due to the fast pre-warming through the cooling system can especially be observed at the piston cluster, fast pre-warming reduces friction at the pistons. The warmed-up engine requires less starting power, which even the cold battery can provide. This way the battery is also taken more care of by the engine requiring a smaller load.

Aspects of reliability and care are a firmer engine start due to the more favourable conditions of burning and self-ignition in the cylinders and a reduced engine friction due to the rapid attainment of the working temperature, respectively.

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List of Symbols

ϑ_m	Temperature of engine parts in contact with water (average cylinder wall temperature)
ϑ_{v1}	Temperature of the coolant leaving the engine
ϑ_{v2}	Temperature of the coolant entering the engine
ϑ_{o1}	Temperature of the oil leaving the heat exchanger
ϑ_{fv}	Phase changing temperature
ϑ_k	Ambient temperature
ϑ_t	Average temperature of the heat storage unit
ϑ_{t0}	Average temperature of the heat storage unit at the beginning of engine pre-warming
ϑ_{m0}	Average temperature of the engine at the beginning of engine pre-warming
ϑ_g	Temperature of the exhaust gas
$(mc)_m$	Thermal capacity of the units in the cooling cycle of the engine
$\dot{m}_{ff}$	Mass flow of the coolant during engine pre-warming
R_r	Thermal conductivity of the whole engine pre-warming system
$(kA)_k$	Environment-bound thermal conductivity of the engine and the units in the cooling cycle of the engine
$(kA)_h$	Thermal conductivity of the intermediate heat exchanger
$\dot{Q}_m$	Momentary heating performance of the engine pre-warming realised with the heat exchanger system
P_{start}	Power input of the starter
t	Time