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Heat storage device for pre-heating internal combustion engines at start-up*

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Abstract—The development of heat storage (HS) devices for pre-heating internal-combustion engines at start-up is presented as an extremely urgent problem. The absence of warm garages and the above-average depreciation of automotive machinery, especially urban buses, force maintenance organisations to search for new ways to facilitate engine start-up in cold periods. In this work, a thermal accumulator (HS) working on the effects of absorption and rejection of heat energy at the solid–liquid phase-change of the heat storage substance is discussed. In the theoretical part, a numerical method for calculating heat storage and the characteristics of heat storage devices is described. The experimental part describes the laboratory installation simulating conditions for the working of the HS device and presents the results of laboratory experiments. Data on full-scale tests of pre-heating devices for starting carburettor engines and an analysis of data received are given. © Elsevier, Paris

heat storage (HS) / pre-heating of engine / latent heat of solid–liquid phase change

Résumé — Développement de systèmes de stockage de chaleur pour le démarrage de moteurs à combustion interne. Le développement de systèmes de stockage de chaleur pour aider au démarrage des moteurs à combustion interne est un problème d'actualité. L'absence de garages chauffés et la vétusté des véhicules automobiles, spécialement des bus, contraignent les sociétés de maintenance à rechercher de nouvelles voies pour faciliter le démarrage des moteurs par temps froid. Dans ce travail, une accumulation thermique à changement de phase est étudiée. Dans la partie théorique, une méthode numérique permettant de calculer le système de stockage thermique et ses caractéristiques est décrite. Dans la partie expérimentale, l'installation de laboratoire simulant les conditions de travail de l'accumulateur thermique et les résultats obtenus sont présentés. Les caractéristiques d'un système réel de préchauffage pour un moteur à carburateur et les analyses correspondantes sont données. © Elsevier, Paris

stockage thermique / préchauffage de moteur / chaleur latente de changement de phase solide-liquide

Nomenclature

c_l	specific heat of the heat transfer fluid	$J \cdot kg^{-1} \cdot K^{-1}$
c_i	specific heat of component i of the engine	$J \cdot kg^{-1} \cdot K^{-1}$
c_t	specific heat of phase change material	$J \cdot kg^{-1} \cdot K^{-1}$
c_w	specific heat of the capsule wall	$J \cdot kg^{-1} \cdot K^{-1}$
d	width of the cavities for the uniform passing over of the capsules by circulating liquid	m
d_{eqv}	equivalent diameter of pipe	m
g	volumetric flow rate of the heat transfer fluid	$m^3 \cdot s^{-1}$
Gr	Grashof number	
H	latent heat of phase change material	$J \cdot kg^{-1}$
L	length of capsules	m
m_i	specific weight of components of the engine	$kg \cdot m^{-3}$
n	quantity of capsules	
Nu	Nusselt number	
p	power	
P_l	density of the heat transfer fluid	$kg \cdot m^{-3}$
P_t	density of phase change material	$kg \cdot m^{-3}$
P_w	density of the capsule wall	$kg \cdot m^{-3}$
Pr	Prandtl number	
Pr_f	Prandtl number of the film	
q	heat flux	W

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Q_3	heat rejected from heat transfer fluid in the volume V_1	J
r	radius of the capsules	m
r_1	radius of phase change border at local moment	m
R	radius of the heat storage envelope	m
Δr	thickness of the capsule wall	m
t	time	s
ΔT	temperature difference average-logarithmic temperature gradient	K
Δt_i	crystallisation time of a layer of thickness Δx	s
T_{in_0}	temperature of the engine before the beginning of the HS discharging	K
T_{p}	melting temperature of phase change material	K
V_1	volume of liquid in heat storage	m^3

Greek symbols

λ_{w}	thermal conductivity of wall material of capsules	$\text{W·m}^{-1}\text{·K}^{-1}$
λ_{t}	thermal conductivity of phase change material	$\text{W·m}^{-1}\text{·K}^{-1}$
σ_{t}	time-dependent thickness of solidified	m

1. INTRODUCTION

Heat storage devices (abbreviated to HS) mounted on automobiles permit the elimination of numerous negative factors, connected with the 'cold' engine start-up. These include increased amounts of fuel, large concentrations of CO in the exhaust, and a decrease in engine response.

HS devices should have high power capacity, small dimensions and vibration resistant design in order to meet the conditions of bus operation.

The Porous Media laboratory developed, made and tested an experimental HS sample for an urban bus 'LAZ-695 N'.

This HS works on the basis of effect of phase-change, followed by the rejection and absorption of the latent heat of the phase change. This approach provides high density of storage energy with reasonably stable exit temperatures of the HS.

The basis of any HS device is a heat storage material or phase change material (PCM). For low-temperature ranges, the following PCMs are the most appropriate: $Na_2CO_3{\cdot}12H_2O$, $NaCH_3$ $CaO{\cdot}3H_2O$, $NaOH{\cdot}H_2O$, $Ba(OH)_2{\cdot}8H_2O$, $LiNO_3{\cdot}3H_2O$ [1].

As to the material of the HS envelope, corrosion properties show [2,3] that crystal-hydrates of salts are compatible with stainless steel with Cr–Ni additives. Among polymer materials, the most suitable is polyethylene.

2. NUMERICAL MODEL

We developed an engineering technique for the calculation of the automobile HS parameters, in the capsule design, at longitudinal flow of capsules.

For the calculation of the HS parameters, the following sequence of actions was realised. Firstly, we defined the heat quantity necessary for the heating of the engine at temperature ΔT:

$$Q = \sum_i c_i m_i \Delta T \tag{1}$$

where c_i and m_i are the specific heat and weight of components of the engine respectively.

After setting the determining sizes of a design (*figure 1*), i.e. the radius R of the HS envelope, the radius r of the capsules, the thickness Δr of the capsule wall, the width d of the cavities for the uniform passing over of the capsules by circulating liquid, and also the thermal properties of the PCM, the capsule material, the heat transfer fluid, the geometrical dimensions and specific heat of materials, we determine the quantity of capsules n, their length L and the necessary amount of PCM m:

$$n = \frac{\pi R^2}{\pi r^2 + 2r^2\left(2\sin 60^\circ - \dfrac{\pi}{2}\right)} \tag{2}$$

$$L = \frac{Q - Q_1}{n\pi (r - \Delta r)^2 P_{\text{t}} H} \tag{3}$$

$$m = n\pi (r - \Delta r)^2 L P_{\text{t}} \tag{4}$$

where P_{t} and H are the density and the latent heat of PCM phase change and Q_1 the quantity of heat saved by the specific heat of materials of the HS device.

The quantity of heat Q_1 is computed from temperature difference $\Delta T_{\text{w}} = T_{\text{p}} - (T_{\text{in}_0} + \Delta T)$, where T_{p} is the melting temperature of the PCM, and T_{in_0} the

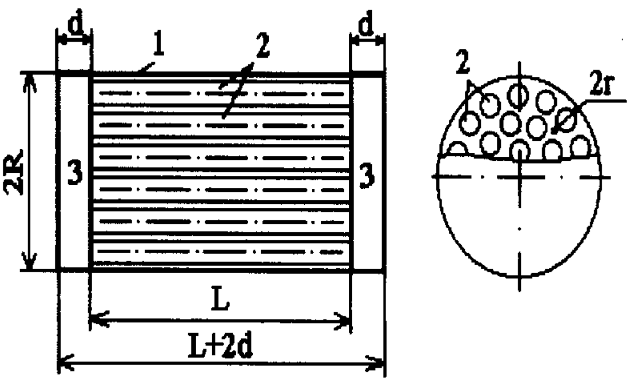

Figure 1. Determining design dimensions of the HS device used in calculations. 1. Envelope of the HS device. 2. Capsules. 3. Cavities for creation of a uniform flow around capsules.

temperature of the engine before the beginning of the HS discharge. At this stage of calculation, we update the dimensions R, r, and d for the definition of the most reasonable ratio of envelope radius R and length of capsules L.

The discharge process rate of the HS is calculated after definition of mass-dimensional characteristics of the HS. The following assumptions were made in the physical model: the crystallisation process of the PCM occurs simultaneously over the whole length of the capsules, and the phase boundary is moving in a radial direction. This is caused by the large temperature drop between the PCM and the heat transfer fluid, when the phase boundary in the axial direction has no time to be generated.

At each moment of time, the temperature distribution in the crystallised PCM layer and the temperature of capsule walls correspond to a temperature distribution in stationary mode. Such simplification is justified by the much lower speed of movement of the border of phase changes in comparison with the speed of movement of an isothermal surface in non-stationary mode.

In the calculations, the average length of the capsules heat transfer characteristics was used. This simplifies calculation and reduces the influence on the results, of any non-uniformity of the solidified PCM layer thickness along capsules.

Specific heat of HS materials if the temperature is higher than that of the phase change was not taken into account in the calculation of discharge process rates.

The specific heat flux transmitted from the PCM to the heat transfer fluid during the process of the HS discharging is defined as [4]:

$$q = h\,\Delta T \tag{5}$$

where ΔT the average-logarithmic temperature gradient:

$$\Delta T = (T_{\text{out}} - T_{\text{in}}) / \ln \frac{T_{\text{p}} - T_{\text{in}}}{T_{\text{p}} - T_{\text{out}}} \tag{6}$$

Overall heat transfer coefficient h for this case is:

$$h = \left(\frac{1}{a} + \frac{r}{\lambda_{\text{w}}} \ln \left(\frac{r}{r - \Delta r} \right) + \frac{r}{\lambda_{\text{t}}} \ln \frac{(r - \Delta r)}{(r - \Delta r - \sigma_{\text{t}})} \right)^{-1}, \tag{7}$$

where λ_{w}; λ_{t} are the thermal conductivities of wall material of capsules and of the PCM respectively and σ_{t} is the time-dependent thickness of the solidified PCM.

Thus, the problem of the discharge process rate calculation, i.e. definition of dependence of a heat flux from time $q(t)$, is linked to the definition of the crystallisation time $\mathrm{d}t$ of an elementary cylindrical layer with thickness $\mathrm{d}r$.

The dependence can be found from the appropriate ratio for the weight of crystallised PCM. On the one hand, weight is proportional to the heat flux from the PCM to the heat transfer fluid:

$$\mathrm{d}m = \frac{2\pi r\, q\, L}{H}\, \mathrm{d}t \tag{8}$$

on the other hand, weight is equal to:

$$\mathrm{d}m = 2\pi r_1\, P_{\text{t}} L\, \mathrm{d}r \tag{9}$$

where r_1 is the radius of phases change border at local moment.

Whence we receive the following expression for time:

$$\mathrm{d}t = \frac{r_1\, P_{\text{t}}\, H}{r\, q}\, \mathrm{d}r \tag{10}$$

To find the heat flux q, it is necessary to define input and output temperatures of the HS: T_{out} and T_{in}.

$$T_{\text{out}} = T_{\text{in}} + \frac{2\pi P_{\text{t}}\, r_1\, LH\, \mathrm{d}r + Q_2}{c_1\, g\, P_1\, \mathrm{d}t} \tag{11}$$

where P_1; c_1 and g are the density, specific heat and the volumetric flow rate of the heat transfer fluid respectively:

$$Q_2 = 2\pi L \left[P_{\text{t}} c_{\text{t}} \int_{r_1}^{r - \Delta r} \Delta T_1(r)\, r\, dr + P_{\text{w}} c_{\text{w}} \int_{r - \Delta r}^{r} \Delta T_1(r)\, r\, dr \right] \tag{12}$$

The value Q_2 takes into account the quantity of rejected heat which was conserved in the materials of the capsule by the specific heat; $\Delta T_1(r)$ is the temperature difference of elementary layers of the capsule at increase of thickness of crystallise layer on value $\mathrm{d}r$; P_{t}, c_{t}, P_{w}, c_{w} are the density and specific heat of the PCM and of the capsule wall respectively.

In case of the temperature distribution for a stationary mode, the sum of the integrals (12) is calculated analytically and reduces to the problem of finding the inner and external wall temperatures of the capsule.

The temperature T_{in} depends on time, and is defined by the amount of heat $Q = Q(t - t_0)$ (Q is a function of the time) extracted from HS to heat transfer fluid at time $t - t_0$, where $t_0 = V/g$ is the time of the heat transfer fluid replacement in a cooling jacket of the engine with volume V. The dependence temperature on an input of the HS as a function of the time is defined by the equations:

For $t < t_0$ $\qquad T_{\text{in}} = T_{\text{in}_0}$

For $t_0 < t < t_0 + V_1/g$

$$T_{\text{in}} = T_{\text{in}_0} + \frac{Q_3\, g}{V_1 \sum_i m_i\, c_i}(t - t_0), \tag{13}$$

where Q_3 is the heat rejected from heat transfer fluid in the HS volume V_1 on cooling down from melting temperature T_{p} to temperature $T = \dfrac{T_{\text{p}} V_1 c_1 P_1 + \sum_i c_i m_i T_{\text{in}_0}}{V_1 c_1 P_1 + \sum_i c_i\, m_i}$.

For $t > t_0 + V_1/g$

$$T_{\text{in}} = T_{\text{in}_0} + T + \frac{Q_4}{\sum_i c_i\, m_i} \qquad (14)$$

where Q_4 is the amount of heat (Q_4 is a function of time) extracted from HS to heat transfer fluid at time $t = t_0 - V_1/g$.

It is assumed in this mathematical model that crystallisation of the PCM starts at time $t = V_1/g$, i.e. after replacement of the heat transfer fluid in the HS device.

The empirical dimensionless ratio for the Nusselt number for laminar flow in a pipe [5] was applied for the definition of the heat transfer coefficient:

$$Nu = 0.15\, Re^{0.33}\, Pr^{0.43}\, Gr^{0.1} (Pr/Pr_f)^{0.25} \qquad (15)$$

where an equivalent diameter of a pipe is taken as a determining size. For this case:

$$d_{\text{eqv}} = \frac{4\,(2 \sin 60° - \pi/2)}{\pi}\, r \qquad (16)$$

The system of equations (5–7), (10–14) was solved by a numerical iteration method. The quantity of evolved heat Q_i was defined with thickness varying of the solidified layer $\Delta x (r_1 = r - i\Delta x - \Delta r)$, i.e. the crystallisation time Δt_i of a layer of thickness Δx was calculated. The value of the heat transfer coefficient was specified after each step along r taking into account changes in the thermal properties of the heat transfer fluid.

The numerical dependence of heat power as a function of time is represented in *figure 2.*

The results of calculations were used for the design of the experimental prototype HS.

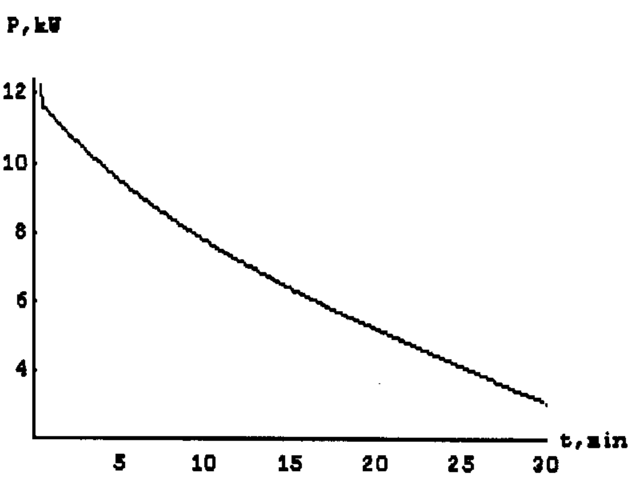

Figure 2. Dependence of heat power as a function of time.

3. DESIGN OF AN EXPERIMENTAL SAMPLE OF THE HEAT STORAGE DEVICE

The experimental prototype of the HS (*figure 3*) consists of three basic parts: the cylindrical envelope, capsules with phase change material (PCM), and the thermal insulation jacket. The height of the HS device without thermal insulation is 420 mm, and its diameter is 300 mm.

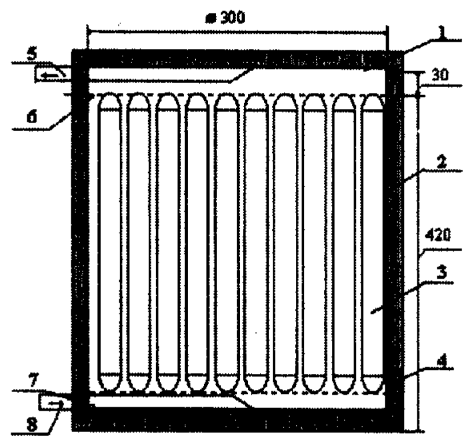

Figure 3. Diagram of the experimental heat storage device. 1. Cover. 2. Envelope. 3. Capsule containing the PCM. 4. Thermal insulation. 5. Outlet pipe. 6 and 7. SS steel mesh. 8. Inlet pipe.

The envelope consists of the top removable cover 1 with an outlet pipe 5 and SS steel mesh 6, and a cylindrical reservoir, in the bottom part of which an entrance pipe 8 and the second SS steel mesh 7 are placed. The SS steel meshes are required for fixing capsules containing the PCM and for the creation of inlet and outlet cavities. The cavities are required for the uniform flow of the circulating liquid over the capsules. SS steel meshes cause the additional turbulence of the liquid inside the channels, and this raises the heat transfer coefficient and accordingly improves dynamic characteristics of heat storage.

Capsules are made from a polyethylene tube PVP 25C with an external diameter of 25 mm. Crystalhydrate $NaOH.H_2O$ with an additive preventing over-cooling of the PCM during the discharging of HS is used as PCM. The temperature of the phase change is 64 °C.

Inside the envelope 109 capsules, all with equal length of 400 mm, are placed.

The thermal insulation consists of 6 beds of synthetic felt and an external cover of polythene.

The summary characteristics of this experimental HS device are:

- quantity of capsules: 109;
- total weight of the PCM: 21.8 kg;

– weight of capsules: 29.4 kg;

– calculated value of heat energy, stored by HS: 7.5 MJ;

– weight of HS device (without thermal insulation): 36.8 kg;

– overall dimensions: 340 × 470 mm.

4. EXPERIMENTAL RESULTS OF THE LABORATORY RESEARCH

The experimental set-up consists of two liquid circulating loops, one for heating and one for cooling, and a measurement system. The first liquid loop contains a thermostat and connecting flexible pipelines. The second loop consists of the pipelines for the connection of the HS device to a water supply system and flow meter.

The temperature measurements were carried out with the help of copper-constantan thermocouples by multi-dot voltmeter. The thermocouples were placed in the inlet and outlet pipes of the HS device, inside the envelope and inside the thermostat.

At the beginning, the HS device heated up to temperature 90 °C. For this purpose the first circulating loop of the set-up is involved.

After a temperature 90 °C had been reached, the HS device is disconnected from the first loop and is connected to the second one. The running water valve is opened and the process of discharging is started. The water from the water-pipe has constant temperature of about 10 °C. The outlet water initially has temperature close to the temperature of the working substance of the HS device, then it is gradually reduced and finally reaches the temperature of the cooling water.

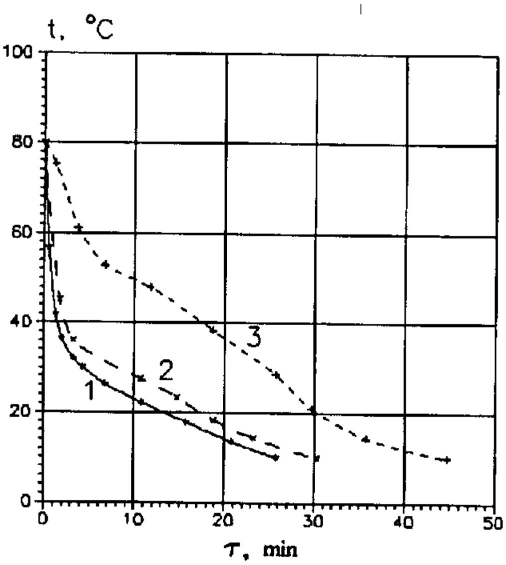

Figure 4. Change in water temperature of the HS device output during the discharging process (with water drained prior). Water flow rate: (1) 7.3 $L \cdot min^{-1}$, (2) 5.4 $L \cdot min^{-1}$, (3) 2.15 $L \cdot min^{-1}$.

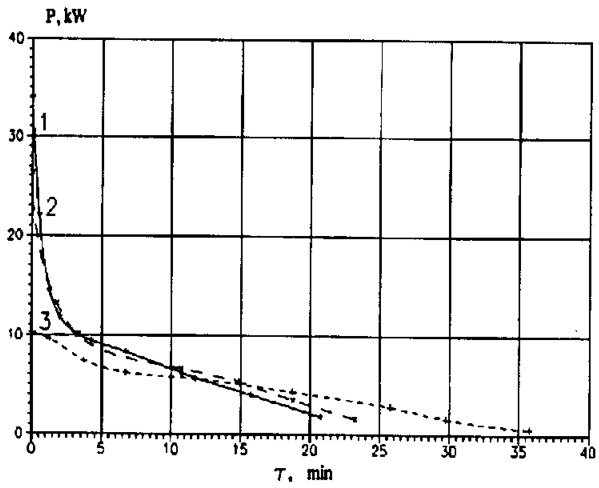

Figure 5. Dependence of heat power, rejected by the HS device, versus time (with water drained prior). The flow rate of the water: (1) 7.3 $L \cdot min^{-1}$, (2) 5.4 $L \cdot min^{-1}$, (3) 2.15 $L \cdot min^{-1}$.

Figure 4 shows dependencies of outlet temperature of water versus time, for the discharge process. Water was first of all drained from the HS device. The research was carried out using water-flow rates of 7.3, 5.4 and 2.15 $L \cdot min^{-1}$.

The change of heat power P as a function of time is represented in *figure 5*. The curves obtained exhibit clearly a maximum of P in the initial period. The higher peak was obtained for discharging without draining the circulating water. Comparison of the experimental curve 1 (*figure 5*) and the calculated curve (*figure 2*), which was obtained under the conditions of the experiment shows satisfactory agreement of the experimental and theoretical data.

During the experiments the quantity of heat rejected during the discharge period was defined. For the case in which the water was not drained, it was 13 MJ, and for second case where the water was drained, it was 10.5 MJ. Hence, it is possible to draw conclusions about the significant stock of thermal capacity of HS, sufficient for start-ups of the 'cold' bus engine.

Summary results of laboratory tests are given in *tables I* and *II*.

The value of thermal energy which is necessary for the pre-heating and reliable start-up of the engine from a 'cold' state is 1.6 kWh.

On the basis of the laboratory test results it is possible to conclude that the working parameters of the HS device are comparable with calculated results.

TABLE I
Results of the HS tests without water drain.

Flow rate of water ($L \cdot min^{-1}$)	Average heat power (kW)	Peak of the heat power (kW)	Time of discharging (min)	Time, required for the bus engine pre-heating (min)
8.3	10	43	21	4
5.4	7.8	30	25	4.75
2.15	5.4	12	39	9

TABLE II
Results of the HS tests with previously drained water.

Flow rate of water ($L \cdot min^{-1}$)	Average heat power (kW)	Peak of the heat power (kW)	Time of discharging (min)	Time, required for the bus engine pre-heating (min)
7.3	8	34	20	8
5.4	7.3	26	22	8.45
2.15	4.9	10	31	13.25

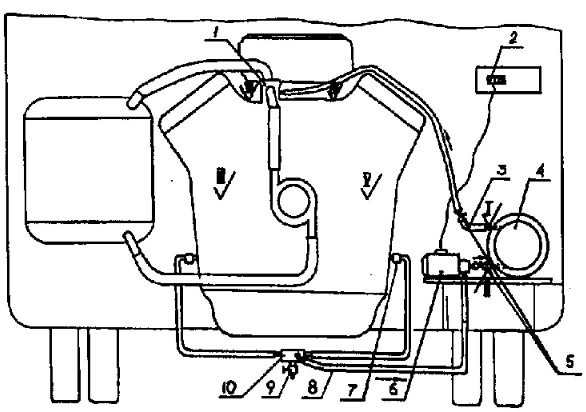

Figure 6. Diagram of the location of the experimental HS device in the bus LAZ-695N. 1. Thermostat. 2. Control block of electrical pump. 3. Outlet pipe of HS device. 4. Heat storage device (HS). 5. Valves. 6. Electrical pump. 7. Union. 8. Inlet pipe of HS device. 9. Draining valve. 10. T-pipe.

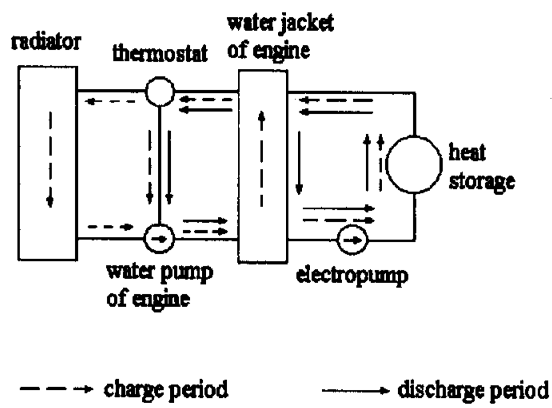

Figure 7. Diagram of connection of the HS device to engine cooling system.

5. OPERATIONAL TESTS

5.1. Location of HS device experiments in the bus

The experimental device for start-up pre-heating of the engine (*figure 6*) consists of the heat storage device 4, an electrical pump 6 with the control block 2, inlet and outlet pipes 8 and 3 with valves 5. The outlet pipe of the HS is connected to the outlet of a water jacket in front of the thermostat 1. The HS device is located horizontally; the electrical pump is mounted on a single plate and is placed on right side near to the bus saloon.

The basic diagram of the connection of the HS device to the engine cooling system is shown in *figure 7*.

The HS device is connected parallel to the engine water jacket. During the discharge of the device, cooling liquid moves with the help of the electrical pump through the HS device and the water jacket of the engine. A part of the liquid thus passes through a branch pipe of a small cooling loop bypassing the head of the cylinders. This reduces the heating efficiency of the engine slightly; however, owing to the small size of branch pipe, the thermal losses are insignificant. During charging of the HS device when the thermostat is closed, cooling liquid will be simultaneously pumped by the water pump of the engine into a small cooling loop

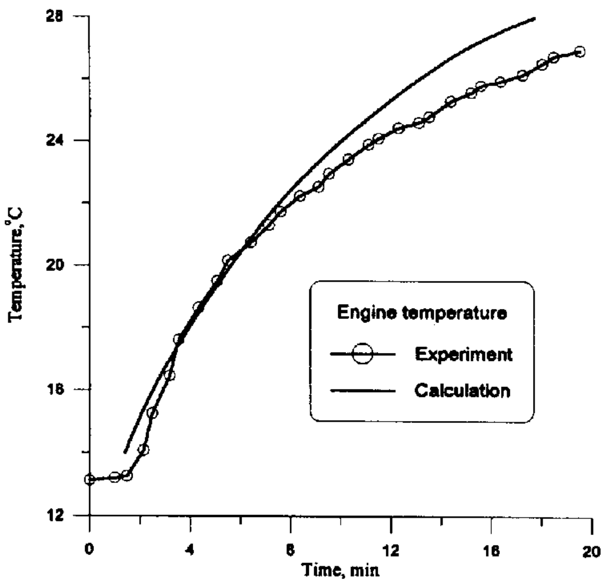

Figure 8. Dependence of the engine temperature versus discharge time.

of the engine and the HS device. After the thermostat opening temperature has been reached, the heat transfer fluid starts to be pumped through a radiator (big cooling loop). During the period when heat is stored, the valves 5 (*figure 6*) are closed, preventing the natural convection circulation of liquid through the cooling system.

5.2. Preliminary operational test results

Preliminary operational tests were carried out under different regimes of the HS operation. Regimes differed in the conditions and periods of heat keeping, discharging and charging. The operation of the experimental HS device in full-scale conditions was monitored using 6 copper-constantan thermocouples (*figure 6*).

The temperature history of the engine during discharging is represented in *figure 8*. Some overestimation of theoretical values is caused by heat losses to the surrounding environment.

Thus, preliminary operational tests have shown the validity of the application of the engineering technique developed for the calculation of heat storage parameters. Resumption of operational tests is planned in the winter period.

6. CONCLUSION

The result of this study is the practical confirmation of theoretical developments regarding the facilitation of heat storage in the start-up of an internal-combustion engine by heating the engine from the energy stored in a heat storage device.

The use of a mathematical model allowed us to determine design data and the operational characteristics of heat storage. An experimental set-up was created to check the theoretical results and to modify the design data. It is certain that true experimental data can be obtained only from the real-life operation of the HS device placed in automobile machinery.

An HS device based on absorption and extraction of latent heat from phase change was mounted on an urban bus and operated under real conditions. The analysis of experimental data at the laboratory and of the data obtained in real conditions allowed us to make appropriate modifications to design a full scale HS device.

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