Configuration and algorithm of the liquid circulation control system in the cooling system with a heat accumulator

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Abstract. In this article authors presented the configuration and algorithm of the liquid circulation control system a modified cooling system. The vehicle selected for modification and simulation is the Toyota Yaris Hybrid. Modification of the cooling system in a hybrid vehicle consisted of the use of a Heat Storage (HS) and Heat Exchanger exhaust gases-cooling liquid (HE). Waste heat from exhaust gases has been stored in HS and used to obtain and maintain the desired operating temperature Internal Combustion Engine (ICE), while his intermittent operation. The purpose of the proposed amendment is increase energy efficiency of the hybrid vehicle`s propulsion system by reducing the operating time of the ICE at a temperature lower than the assumed working temperature. The control system is based on the C-RIO real time computer and the LAbVIEW software. The software controls the circulation of the cooling liquid and exhaust gases and also allows the recording of the relevant parameters of the hybrid drive system, such as e.g. the temperature of the HS, the load of ICE, ambient temperature or temperature of exhaust gases before HE. The paper presents the results of simulation of signal changes to control the cooling system. Simulations of control system were carried out for winter conditions of the surroundings and urban traffic, including heat received from the cooling system to warm the passenger space. In the further stage of the research, the authors plan to carry out road experimental research.

1. City traffic cause difficulty in obtaining and maintaining the desired operating temperature of the ICE

Hybrid Electric Vehicle (HEV) in city traffic is characterized by intermittent operation of the ICE with long pauses, which causes difficulty in obtaining and maintaining the desired operating temperature of the ICE, especially at low outdoor temperatures and intensive use of the heating passenger space the HEV. The result is the increased emission of noxious exhaust gas components and increased fuel consumption. Based on previous studies of authors, included in the paper [2], the result of research is shown in figures below. The first of the following images shows the temperature of the coolant and load of ICE during urban driving for Toyota Yaris Hybrid. The temperature is in the range around 10°C. Measurements continued until the stabilization of temperature of the working medium to the value specified by the manufacturer (86°C).
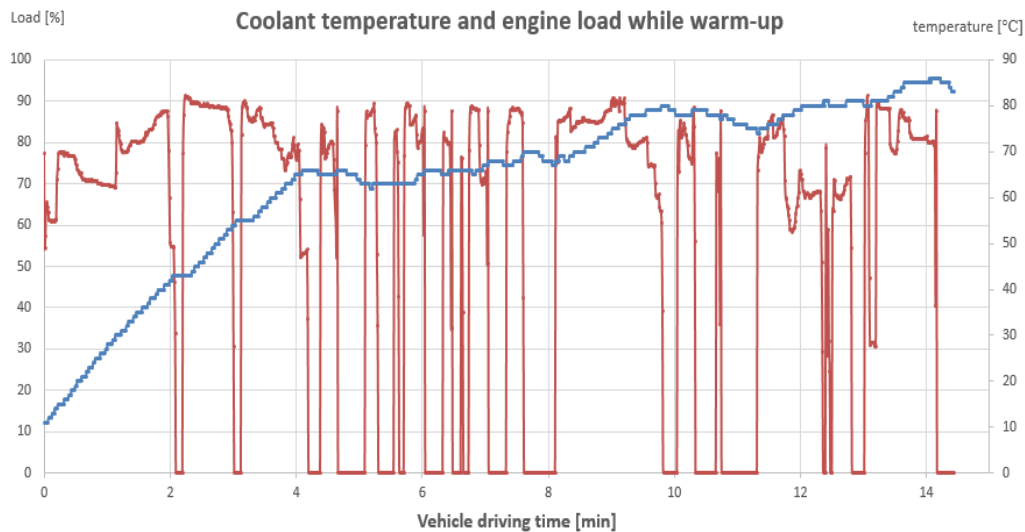
Figure 1. The ICE load and coolant temperature while warm-up

The second of the images demonstrated engine coolant temperature changes, after warming up, while driving in urban conditions, with turn-on heating of the passenger spare. You can notice a clear drop in the temperature of the coolant during breaks in the operation of the ICE. It is caused by the dissipation of heat from the ICE to the environment and its transfer from the cooling system to the passenger space. Data marked with a digit [1] have been collected during tests at an external temperature of -15°C, while data with [2] at an external temperature -5°C, at the similar traffic conditions. In both cases, a drop in the temperature of the coolant below the value depending on the ambient temperature forces the engine to start to warm up.
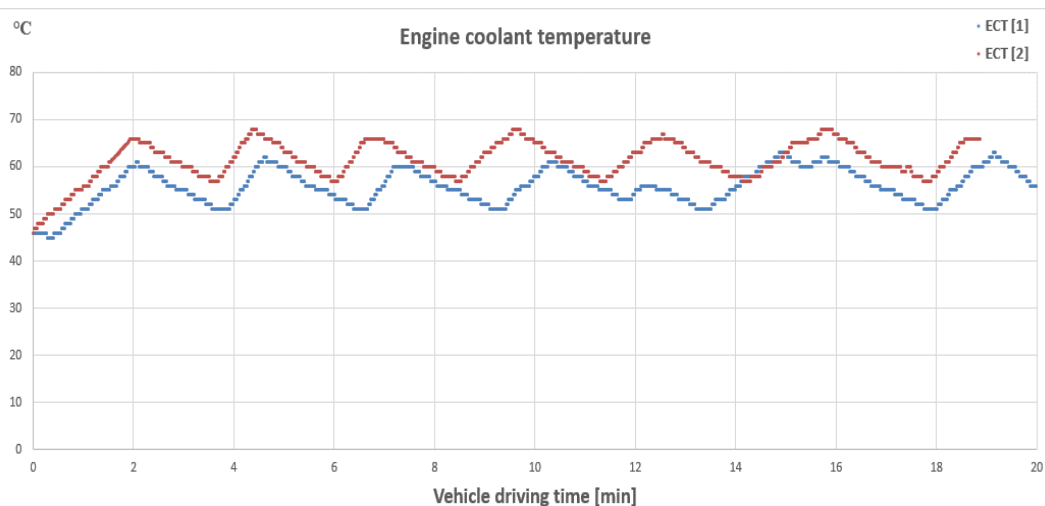

Figure 2. The results of road test for warm start Toyota Yaris Hybrid

Result of this unnecessary engines starts is the increased emission of noxious exhaust gas components and increased fuel consumption. Research on the impact of the use of a heat accumulator on the emission of toxic components, among others M. Brzeżański and published the results in the publication [1].

2. Modify the cooling system

Warming up of the ICE in HEV to operating temperature is a long process, especially during urban traffic. The proposed solution to this problem is to apply HS in the cooling system. The waste heat is stored from exhaust gas, by the cooling system, and used to obtain and maintain the internal combustion engine's nominal operating temperature. The diagram of the modification of cooling system is presented in the figure below.
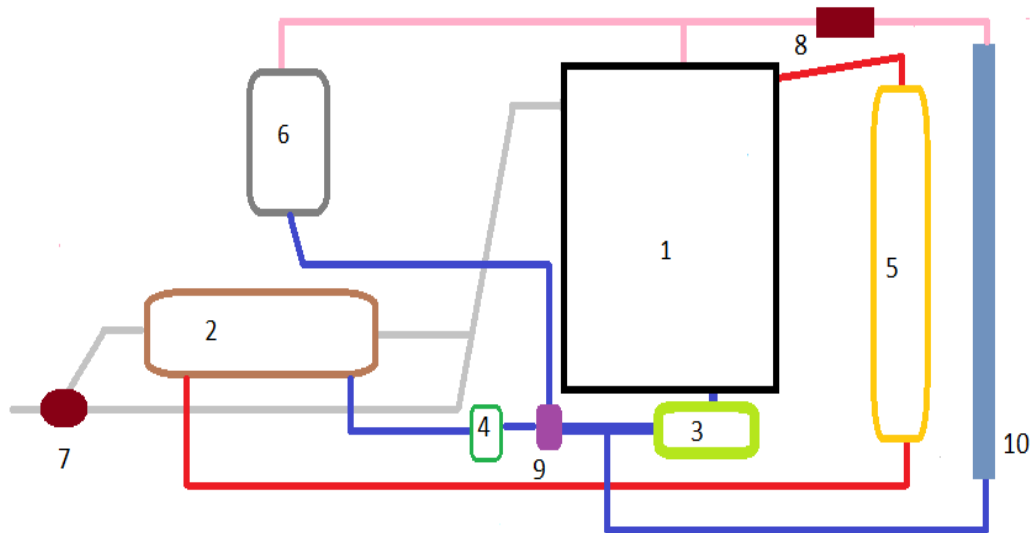
Figure 3. Components of the cooling system: 1- ICE, 2 - HE, 3 - main coolant pump, 4 - additional coolant pump, 5 - HS, 6 - passenger space heater, 7 - exhaust gas dampers, 8 - thermostat, 9 - three-way coolant valve, 10 – radiator

Three-way valve, exhaust gas dampers, HS, additional electrical pump and HE are elements that the article's author added to the engine cooling system designed by the vehicle manufacturer. In a phase of the heat transfer, the coolant absorbs the thermal energy from the heat accumulator and releases it in the ICE cooling jacket, especially the ICE head. The heat capacity of the heat accumulator should be chosen so as to ensure effective heating of the cold ICE. Too low heat capacity will be not achieved the intended increase in ICE temperature during warm-up. At the same time, oversizing the heat accumulator can lead to difficulties in fully charging the HS, which results in low efficiency and high thermal energy discharge.

$$Q_W = \int_i^N cw_i \, m_i \Delta T + \Delta Q_W, \qquad (1)$$

where:

Q_w – amount of heat stored in the ICE [kJ],
cw_i – specific heat of ICE components [kJ/kg*K],
m_i – mass of ICE components [kg],
ΔT – temperature changes [K],
ΔQ_w - heat lost during warm-up ICE [kJ].

Heat lost, in the form of dissipating heat to the environment, they depend primarily on ambient temperature, the time of heating the engine by HS and air circulation in the engine compartment (strongly dependent on the vehicle speed). An extending the time of warming- up the ICE causes an increase in the loss of heat dissipated to the environment. However, shortening the heat transport time results in a reduction of the total heat that the HS is able to transfer to ICE. This is due to the limitation of the heat flux value, through the mass flow of the coolant as well as the thermal power of the HS. The amount of heat dissipated loss also depends on the ambient temperature, the lower it is, the more these losses increase. The increase in air movement in the engine compartment has a similar effect. Air movement in engine space depending strongly of vehicle speed. Example of dissipation of heat to the

environment is illustrated in the picture below, which shows the dependence of the temperature of the cooling liquid in the ICE head from time. This test was carried out for an external temperature of -20°C, a vehicle speed of 60 km/h and switched off heating of the passenger space. The end of the test occurred when the engine temperature dropped to a value 60°C. Then the ICE was forced to start to warm up.
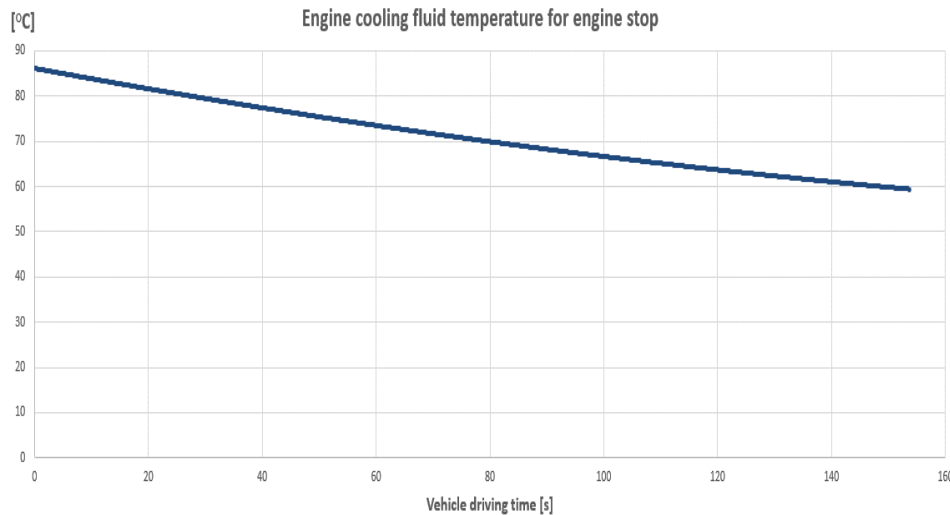
Figure 4. Decrease of cooling liquid temperature for the ICE being switched off

3. Elements of the system controlling the modified cooling system

The control system is based on the C-RIO real time computer and the LabVIEW software. The software controls the circulation of the cooling liquid and exhaust gases and also allows the recording of the relevant parameters of the hybrid drive system. The hardware of control system includes an additional electric cooling fluid pump, three-way control valve for cooling fluid, four thermocouple temperature sensors, pressure sensor and exhaust gas dampers. The software, based on LabVIEW FPGA module. For reading temperature signals used measuring card NI 9211, for load of ICE and vehicle speed NI 9219. Control of executive elements takes place through control card NI 9263. Real-time computer is powered from the on-board battery. The control system is activated automatically when Hybrid Synergy Drive is reaches the "ready-to-drive" status.

For proper control of the modified cooling system it is necessary following signals to the control system: coolant temperature at the coolant outlet from the HS, coolant temperature at the coolant outlet from the HE, ambient temperature, temperature at the coolant outlet from the ICE, absolute intake manifold pressure, vehicle speed, Hybrid Synergy Drive system status and mode of passenger space heating.

Based on these signals, the control system performs one of three modes:

    a) accumulating the waste heat from exhaust gases in the HS during the operation of the ICE,

    b) warming up the engine with the heat accumulated in the HS before start and during the operation of the ICE,

    c) maintaining the nominal operating temperature of the ICE during breaks in its operation.

Accumulating heat in the heat storage

The conditions necessary to initiate the charging process of the heat accumulator are as follows: ICE in state ON, load of ICE below limit value, temperature of HE and temperature of HS performs the following inequalities:

$$T_{HS} < T_{HS1} - \Delta T_1 \tag{2}$$
$$T_{HE} + \Delta T_1 > T_{HS} \tag{3}$$

where:

T_{HS} - actually temperature of heat storage [°C],

T_{HS1} - phase change temperature of the active material of the HS [°C],

ΔT_1 - temperature hysteresis, preventing the unnecessary circulation of liquid through the HS without heat exchange [°C].

It`s the value of the outside temperature function and vehicle speed; a drop in ambient temperature and increase vehicle speed causes hysteresis to increase. This is caused by an increase in heat losses to the environment in both cases.

Completely perform all of these conditions enables the control system to activate the following: switch-on additional electrical coolant pump, opening the exhaust gas flow through the heat exchanger and opening of the cooling liquid flow through a three-way valve to circuit the HE - HS. After exceeding the threshold defined by inequality (3) below, by controlling the dampers in the exhaust system, the flue gas stream is changed (bypassing the heat exchanger). Then lowering the temperature of the cooling liquid at coolant outlet from the HE below the required inequality (4) value turns off the additional electric liquid cooling pump and closing the three-way valve to circuit the HE – HS.

$$T_{HS} > T_{HS1} + \Delta T_1 \qquad (4)$$
$$T_{HE} < T_{HS} + \Delta T_1 \qquad (5)$$

where:

T_{HE} - temperature of cooling liquid at coolant outlet from the HE [°C].

Compliance with condition (4) means full charging of the heat accumulator. After the HS charging mode has been initiated, the control system continuously checks condition expressed by inequality (5). In case the HS charging is interrupted by condition (5), the control system turn-off additional electrical coolant pump and closes circulation by three-way valve. This is to prevent unnecessary discharge of the HS by dissipating circulating heat to the environment.

Additionally, with the active heat accumulating function in the HE, exceeding the load of the ICE over the permissible value causes a change in the exhaust gas stream (bypassing the heat exchanger). This prevents an increase in flow resistance of the exhaust gases at high engine load, which could affect the conditions of his work. In this case, the operation of the additional coolant pump depends on the condition (3).

Warming up the ICE

The ICE heating processing depends on the state of charge of the HS, which is recognized by inequality (2). If the temperature of the HS performs this inequality, it means that it is not fully charged. For full charged HS heat transfer from the HE to the ICE takes place after the following conditions are perform: the Hybrid Synergy Drive is in state "ready for driving" and the ICE coolant temperature is below the condition (6):

$$T_{ICE} < T_{HS} - \Delta T_2 \qquad (6)$$

where:

ΔT_2 - temperature hysteresis, preventing the unnecessary circulation of liquid from the HS to ICE without heat exchange [°C].

It`s the value of the ambient and ICE coolant temperature and vehicle speed function. For a semi-warm engine, the hysteresis value increases, similar to the decrease in ambient temperature. For increase vehicle speed, the hysteresis is also increases. This is to prevent unnecessary discharge of the HS by dissipating circulating heat to the environment.

The engine preheating process is completed when one of the following (7) and (8) conditions is performed. Exceeding the temperature T_{ICE1} by the coolant of the ICE means heating it up to the set operating temperature, whereas performed conditions (8) means discharging the heat accumulator. In both cases, the additional coolant pump is switched off and three-way valve closes circulation by HE-HS-ICE.

$$T_{ICE} > T_{ICE1} \qquad (7)$$

$$T_{ICE} > T_{HS} - \Delta T_2 \tag{8}$$

where:

T_{ICE1} - engine temperature, considered as its normal operating temperature [°C].

It depends on the outside temperature. For lower ambient temperature, ICE normal operating temperature is decreases.

In case of discharging the HS (8), charging HS cycle takes place after performed conditions, specific to this state.

Heat transfer from the HE to the ICE for part of discharged HS takes place after the three conditions are perform: the Hybrid System Drive is in state "ready for driving" and both inequalities (9) and (10):

$$T_{HS} > T_{amb} + 4\Delta T_2 \tag{9}$$
$$T_{ICE} < T_{HS} - 3\Delta T_2 \tag{10}$$

For this operation, ICE warming-up process is stopped when (8) condition is performed. The ICE coolant temperature as function of time for different values of an ambient temperature is shown in figure 5 for full charged HS.
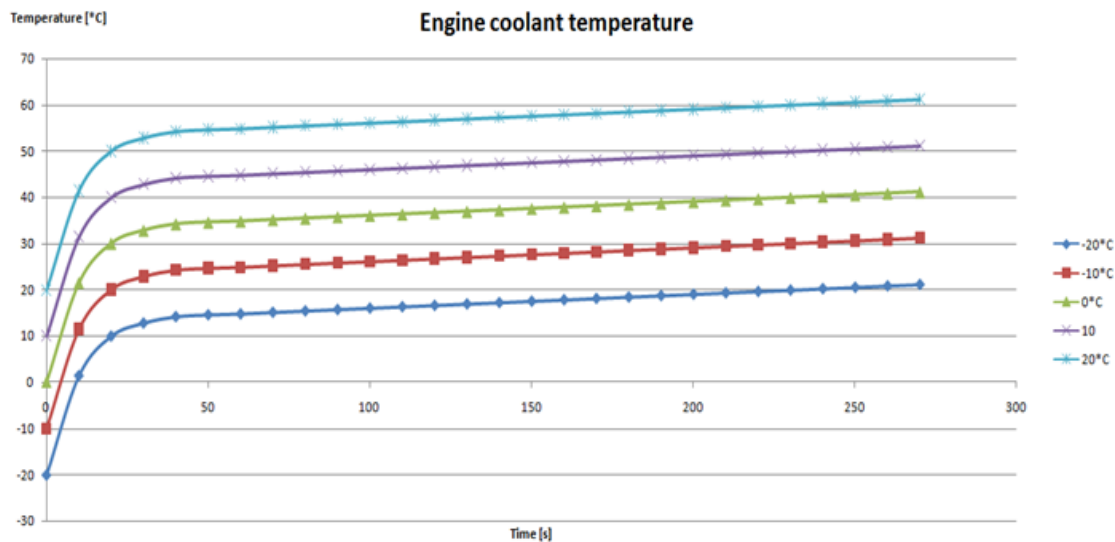
Figure 5. ICE coolant temperature during warming-up depend of ambient temperature

Maintaining the nominal operating temperature of the ICE

The heat capacity of the HS may be used as a buffer, preventing a drop in the ICE coolant temperature. This phenomenon observed during road tests of the Toyota Yaris Hybrid, when the ICE off on figure 2. In this case, the heat transferred from the HS to the cooling system is to compensate for the heat losses of dissipation to the environment and heating of the passenger space. The amount of heat dissipation losses and the amount of heat needed to heat the passenger space are the basis for further research by the authors. Based on previous measurements and vehicle data, we can determine the amount of heat that the cooling system gives during engine breaks. For research, were performed at ambient temperature -15°C, we know the temperature drop in the cooling liquid in the ICE head.

$$\Delta Q_e = \int_i^N c w_i \, m_i \Delta T \tag{11}$$

$$W_e = \frac{\Delta Q_e}{t} \tag{12}$$

where:

ΔQ_e - heat lost from the ICE cooling system during engine stop [kJ],

cw_i - specific heat of ICE components, aluminium-0,84 [kJ/kg*K]; cast iron-0,42 [kJ/kg*K]; coolant-3,94 [kJ/kg*K],

m_i – mass of ICE components [kg],

ΔT - coolant temperature drop, for ambient temperature -15°C it`s around 10 [K],

W_e - average loses heat flux [kW],

t - time while ICE stop [s].

Table 1. Mass and heat capacity of basic engine parts

Components	mass	heat capacity
ICE head	8kg	6,72 kJ
ICE crankcase	29kg	24,36 kJ
Four rods	2,4kg	1 kJ
Crankshaft	3,8kg	1,6 kJ
Four pistons	1,6kg	1,35 kJ
Coolant	2,6kg	10,25 kJ

Substituting data for the equation (11) we get the approximate value of heat released from the cooling system around $\Delta Q_e \approx 450$kJ. The average value of the heat flux is $W_e \approx 2,9$kW. It follows that the thermal power of the HS must be at least greater than average lost heat flux. Higher thermal power of the HS allows for faster heat replenishment during charging mode.

4. Parameters of the modified cooling system

As a HS, the authors chose model A, which is heat in bulkheads in the form of a Phase Change Material (PCM). The active material of the accumulator is barium hydroxide $Ba(OH)_2 \cdot 8H_2O$. It is characterized by high heat of phase change and temperature of phase change within the range of normal operating temperatures of the ICE. The same material was used in the research carried out by O. Schatz [4]. Some of the properties of this material as well as the modified cooling system are shown in the table 2.

The thermal capacity of the HS can be determined from dependencies (1). To simplify the calculation author accepted:

1. lack of heat loss between the HS and the ICE,
2. ideal heat transfer through the coolant,
3. while heating the all ICE cooling system thermal loses has been change from 0 to 2,9kW.

Table 2. Parametric of modified cooling system

System volume	3,4 l stock	5,2 l with HS
Specific heat of coolant fluid	3,94 kJ/kg*K	
Density coolant fluid	1,065 g/cm^3	
Density PCM		2,18 g/cm^3
Latent heat of phase change		285 kJ/kg
Specific heat of PCM		2,28 kJ/(kg*K)
Temperature of phase change		78°C

Substituting data from Tables 1 and 2 in equation (1) for ambient temperature -20°C we get the thermal capacity of the HS $Q_w \approx 2{,}75$MJ (the engine has been warmed to at least 40°C):

$$Q_w = c_{pcm} m_{PCM} + m_{PCM} c_w \Delta T_{HS} \tag{13}$$
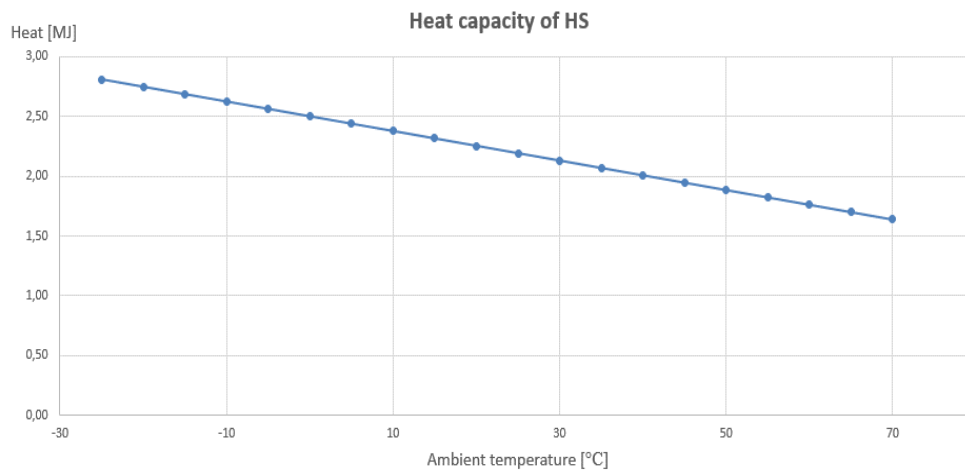
where:

m_{PCM} - mass of active phase change material in accumulator [kg],

c_{pcm} - latent heat of phase change [kJ/kg],

c_w - specific heat of PCM [kJ/kg*K],

ΔT_{HS} - difference between the temperature of the phase change of the HS material and the coolant temperature at out of ICE (before starting the engine it is equal to the ambient temperature) [K].

For the selected PCM it`s means mass of active material above 5,4 [kg], taking into account heat contained in the phase change and latent heat.

Figure 6. Heat capacity of heat storage depending on ambient temperature

The heat flux transmitted by the coolant is determined by the dependence (14):

$$W_c = \frac{\Delta T_{HS} q_c c_c \rho}{60} \tag{14}$$

where:

q_c - volume flow of coolant [dm³/min],

c_c - specific heat of coolant [kJ/kg*K],

ρ - density of coolant [g/cm³].

The specific heat coolant transferred from working heat storage during discharge is defined as:
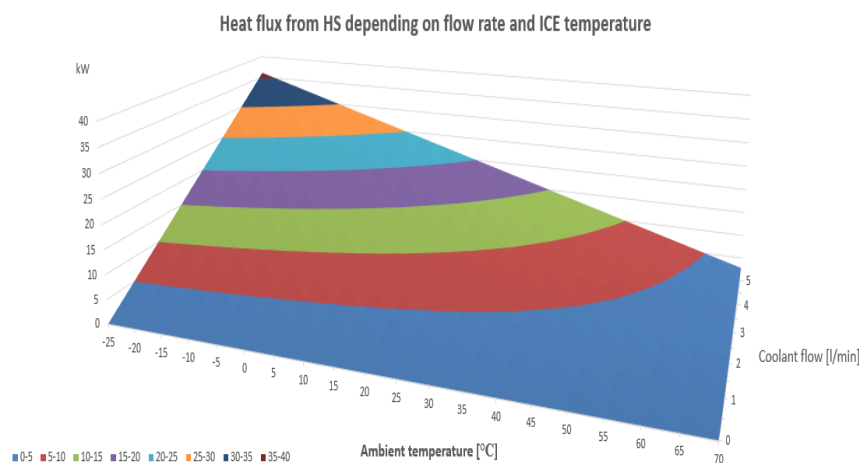
$$q = V \Delta T_{HS} \tag{15}$$

where:

V – volume of coolant flow,

ΔT_{HS} – average-logarithmic gradient:

$$\Delta T = \frac{T_{out} - T_{in}}{ln \frac{T_p - T_{in}}{T_p - T_{out}}} \tag{16}$$

For selected ranges of ambient temperature and volume flow rate of coolant, the heat flux value represents a graph below:

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Figure 7. Heat flux depend on ambient temperature and coolant flow rate

As seen, an increase in ambient temperature reduces the heat transfer through the coolant. For proper value of heat flux, above thermal losses occurring during ICE breaks, it`s necessary to increase coolant flow rate to around 4 [l/min]. Increasing the heat flux for the ICE warming-up mode, because the heat transport time is shortened.

5. Conclusion

The results of simulations in the Matlab program indicate the possibility of shortening the heating time of ICE to working temperature as a result of heating with heat accumulated in the HS. This accumulator collects waste heat from the exhaust system. In the event intermittent operation of ICE, the HS is a buffer to prevent from dropping the coolant temperature in the ICE head. The developed configuration of the control of the heat circuit in the cooling system assumes the control of an additional electrical coolant pump, three-way valve of coolant and throttling valves guiding the exhaust gases. The control algorithm is based on three operating modes: heat storage, ICE warming-up and maintaining operating temperature of ICE during interval of run its. The correct operation of the control system requires the determination of limit values as well as the function of temperature hysteresis. Control of the operation of the control system will be carried out by the authors during road tests, especially in two extreme situations of thermal load: highway driving under conditions of high outside temperature and urban driving in winter conditions. This will allow us to check the correctness of the work in terms of overheating and under heating of the cooling system.

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