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Krmiljenje temperature hladilne vode motorja z notranjim zgorevanjem v preskuševališču

Control of the Cooling-Water Temperature for an Combustion Engine on a Test Stand

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V prispevku je predstavljena rešitev problema s hlajenjem motorja, ki se je pojavil, ko smo preskušali tekočinsko hlajeni motor v preskuševališču za zračno hlajene motorje z notranjim zgorevanjem. Vgradili smo toplotni prenosnik voda-voda in mešalni ventil s pogonom. Krmiljenje odprtja mešalnega ventila in s tem temperature hladilne vode je bilo izvedeno z računalnikom, ki smo ga uporabili tudi za zbiranje podatkov o preskušanju. Sistem je bil preskušen v laboratoriju in omogoča nastavitev želene temperature hladilne vode na vstopu v motor, neodvisno od režima delovanja motorja.

(Ključne besede: motorji ZNZ, hlajenje motorjev, voda hladilna, regulacija temperature)

The solution to an engine-cooling problem, which occurred during the testing of a water-cooled internal combustion engine in a test stand for air-cooled internal combustion engines, is presented in this article. A water-to-water heat exchanger and a control valve were incorporated into an existing engine-cooling system. The cooling-water temperature was controled with a computer, which was also used for the data acquisition. The system was tested in the laboratory and allows to set the cooling-water temperature regardless of the operating regime of the engine.

(Keywords: internal combustion engine, engine cooling, cooling water, temperature regulation)

0 UVOD

Pri preskušanju vodno hlajenih motorjev z notranjim zgorevanjem v preskuševališču za zračno hlajene motorje smo naleteli na problem. Izkazalo se je, da masni tok zraka preko hladilnika motorja ne zadošča za hlajenje. Tudi uporaba dodatnega ventilatorja razmer ni bistveno izboljšala. Najti je bilo treba rešitev, ki bi omogočala zanesljivo in učinkovito hlajenje motorja.

Preskuševališče je opremljeno z absorpcijsko zavoro na vrtinčne tokove, s katero obremenjujemo motor. Mehanska energija se pri tem spreminja v toploto, ki jo je treba prek hladilnega sistema odvesti v okolico. Zmogljivost hladilnega sistema je dovolj velika, da zadošča tudi za hlajenje motorja. Tehnično najmanj zahtevna bi bila neposredna vezava hladilnega kroga motorja na zunanji hladilni sistem. Ta rešitev ni bila primerna, ker v hladilnem krogu motorja uporabljamo destilirano vodo, v zunanjem hladilnem krogu pa mehčano. Naslednja težava je dejstvo, da deluje hladilni sistem motorja pod majhnim nadtlakom (zaprti sistem), medtem ko je

0 INTRODUCTION

While testing a water-cooled internal combustion engine in a test stand designed for air-cooled engines we encountered a problem. It was clear that the air-flow through the original car radiator was insufficient for effective cooling of the engine, and the use of an extra fan did not improve the situation significantly. A solution had to be found that would allow the efficient and reliable cooling of the engine.

The test stand is equipped with an eddy-current dynamometer, which is used for setting an external load. During testing the mechanical energy of the engine is converted into heat, which has to be transferred from the test stand, and therefore a cooling system for the engine dynamometer was necessary. The capability of the dynamometer-cooling system is high enough to allow to cool an engine too. Technically, the least demanding solution would be the direct connection of both cooling systems. But this solution is not appropriate for various reasons. The engine-cooling system uses destilled water, while the dynamometer-cooling system uses softened water. Another problem is that the pressure in the engine-cooling system is a little higher than atmospheric pressure zunanji hladilni sistem odprtega tipa. Kot najboljša rešitev se je pokazala vgradnja toplotnega prenosnika, s katerim smo ločili oba hladilna kroga.

1 IZBIRA IN VGRADNJA TOPLOTNEGA PRENOSNIKA IN MEŠALNEGA VENTILA

Motorska zavora omogoča preskušanje motorjev z močmi do 150 kW, kar pomeni, da bo približno takšen tudi največji toplotni tok, ki ga bo treba odvesti s hladilno vodo. Vgradili smo ploščni toplotni prenosnik Ipros, ki se uporablja v ogrevalni tehniki in ima moč 150 kW. Pri namestitvi toplotnega prenosnika smo izbirali med več možnostmi. Toplotni prenosnik bi bilo mogoče vgraditi namesto hladilnika motorja. Prednost le tega bi bila, da bi nekoliko spremenili tlačne padce v hladilnem sistemu motorja, pomanjkljivost pa, da bi lahko prišlo do pregrevanja motorja, če krmiljenje hlajenja ne bi zadovoljivo delovalo. Zato smo se odločili za zaporedno vezavo. Toplotni prenosnik smo vgradili pred hladilnik. S takšno namestitvijo lahko hladilnik še vedno uporabimo za hlajenje, če krmiljenje ne deluje zadovoljivo. Če je temperatura hladilne vode na vstopu v hladilnik dovolj nizka, da ne pride do vklopa ventilatorja na hladilniku, ima hladilnik majhen vpliv na temperaturo hladilne vode na vstopu v motor. Vgradnja toplotnega prenosnika zahteva tudi izvedbo sistema, ki bo omogočal krmiljenje temperature hladilne vode. Toplotni prenosnik je vezan tako, da sta hladilna voda motorja in zunanja hladilna voda nasprotnosmerni. To pomeni, da bi v primeru, če bi usmerjali celotni masni tok hladilne vode motorja skozi toplotni prenosnik, bila temperatura hladilne vode motorja na izstopu iz toplotnega prenosnika in s tem na vstopu v motor približno enaka temperaturi zunanje hladilne vode. To je za delovanje obremenjenega motorja nezaželeno, ker naj bi temperatura hladilne vode na vstopu v motor pri obremenjenem motorju znašala približno 85 do 90 °C. Zato smo uporabili mešalni ventil, s katerim je mogoče z ustreznim odprtjem nastaviti delež hladilne vode motorja, ki ga je treba hladiti, da bo temperatura na primernem mestu ustrezala želeni. Vgradnja toplotnega prenosnika, mešalnega ventila in lega merilnih točk so predstavljeni na sliki 1.

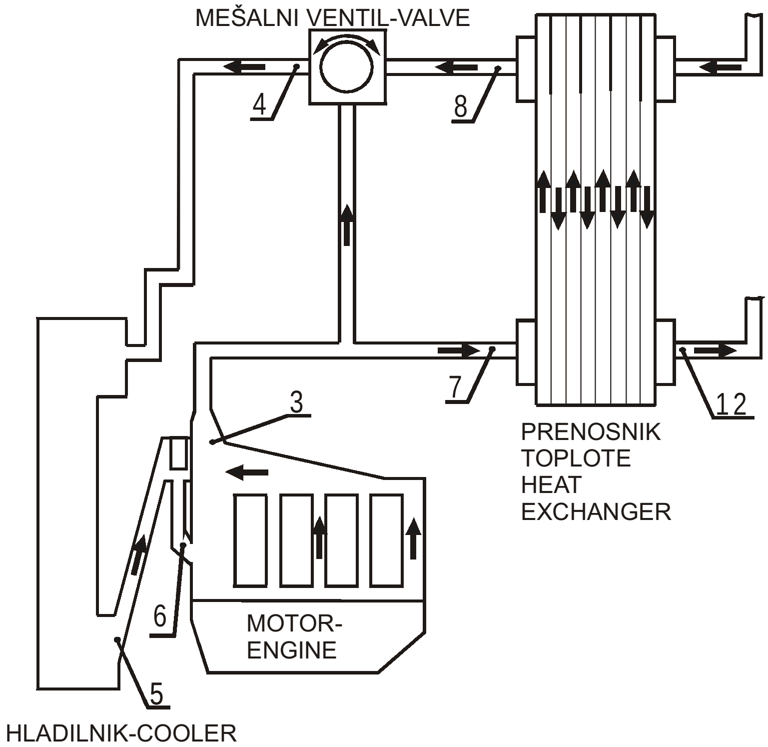
Ker je toplotna vztrajnost motorja dovolj velika, smo izbrali običajni mešalni ventil, ki se prav tako uporablja v ogrevalni tehniki. Izbrali smo tripotni mešalni ventil ESBE 3 G 50. Ta ventil ustreza pričakovani toplotni moči in potrebuje za pogon navor 5 Nm. Tak navor zagotavlja pogonski elektromotor Seltron MP 15. Elektromotor ima največji zasuk 90° in vgrajeni končni stikali v obeh skrajnih legah. Napaja se z napetostjo 230V. Običajni elektromotor potrebuje za polni tek 360 sekund. Z zamenjavo tuljave pa smo ta čas skrajšali na 60 sekund.

(closed system), while the dynamometer-cooling system pressure is equal to atmospheric pressure (open system). The use of a heat exchanger which physically separates both cooling systems, was found to be the best solution.

1 SELECTING AND BUILDING THE HEAT EXCHANGER AND THE CONTROL VALVE

The engine dynamometer allows to test engines with rated powers up to 150 kW, which means that the maximum cooling flux for an engine would be approximately the same. We used on Ipros plate water-to-water heat exchanger with a power of 150 kW that is used in heating installations. There were several possibilities for incorporating the heat exchanger into the engine-cooling system. For example, the car radiator could be replaced with a heat exchanger. The advantage of this solution is a relatively small change in the hydraulic resistance of the cooling system. However, the disadvantage is that the existing radiator provides back up if control of the cooling-water temperature fails. For this reason the heat exchanger was built in ahead of the car radiator, with the heat exchanger and car radiator placed one after another. In this way the radiator could still be used as a backup, and while the fan was switched off it had a negligible effect on the cooling-water temperature. The fan was switched off, if the cooling-water temperature was not too high. The disadvantage of this set up was the increase of the hydraulic resistance. The use of a heat exchanger also required a system to control the temperature of the cooling water. Since the engine cooling water and the external cooling water in the heat exchanger stream in opposite directions, it is possible (if the whole stream of engine cooling water is directed through the heat exchanger) for the engine cooling water to reach the temperature of the external cooling water. That means that the cooling-water temperature can be much lower that required (approximately 85 to 90°C) on its re-entry to the engine. This is why a control valve was built in to control the amount of cooling water to be directed into the heat exchanger so as to reach the desired temperature in a reference position. The heat exchanger, the control valve and the positions of the thermocouples are shown in Figure 1.

Because the heat capacity of the engine was high enough, a standard ESBE 3 G 50 3-way control valve was chosen, this type of valve is also used in heating installations. This valve was matched to the desired power and required an actuator; a Seltron MP 15 standard actuator was chosen. The valve had a maximum angle of rotation of 90°, and had end switches on both ends. It required 230 VDC to operate and needed 360 seconds for a full turn. We modified the actuator to shorten the time for a full turn to 60 seconds.



Sl. 1. *Shematični prikaz hladilnega sistema*
Fig. 1. *Scheme of the cooling system*

2 RAČUNALNIŠKO PODPRTO ZBIRANJE PODATKOV IN KRMILJENJE TEMPERATURE HLADILNE VODE

Pri preskušanju motorjev si prizadevamo, da čim bolj poznamo razmere, v katerih izvajamo preskuse. V ta namen imamo v hladilnem sistemu, preskuševališču in samem motorju nameščene termoelemente (namestitvena mesta so prikazana na sliki 1). Termoelementi so vezani na sistem za zbiranje podatkov, ki skrbi za zapisovanje temperaturnih razmer v preskuševališču. Prav tako sistem za zbiranje podatkov zapisuje tudi vrtilno frekvenco in navor motorja. Pri izdelavi sistema za podporo hlajenja smo poleg dovolj učinkovitega hlajenja imeli v mislih tudi možnost nastavljanja želene temperature na vstopu v motor kakor tudi čim boljše ujemanje dejanske in želene temperature vode na vstopu v motor. Za ta namen je bilo treba izdelati računalniški program, ki bo omogočil dovolj natančno krmiljenje.

Popis razmer, ki vladajo v hladilnem krogu motorja, je težaven. Črpalka za hladilno vodo je vezana na ročično gred motorja. Tako se vrtilna frekvenca črpalke spreminja s spreminjanjem vrtilne frekvence motorja, s tem pa tudi masni tok hladilne vode. Toplotni prenosnik je bilo treba vezati v hladilni krog (prav tako so bile potrebne določene prilagoditve pri vezavi hladilnika), kar je pomenilo uporabo kolen in določene razširitve in zožitve napeljave hladilne vode. Z namenom, da bi zmanjšali prenos vibracij, smo na nekaterih mestih uporabili tudi gumijaste cevi. Iz naštetega lahko, z upoštevanjem dejstva, da nimamo na voljo informacije o kotu odprtja mešalnega

2 COMPUTER-AIDED DATA ACQUISITION AND CONTROLLING THE COOLING-WATER TEMPERATURE

It is important to monitor the events that occur during engine testing. Therefore, several thermocouples were place in the cooling system, the test stand and the engine (see Figure 1). The thermocouples were connected to the data-acquisition system, which automatically stored temperature data on the disk. The same system also acquires data relating to engine speed and torque. In addition to the effectiveness of the cooling system, the possibility of setting the temperature of the cooling water and to keep the temperature as close as possible to the set value was considered during the development of the system. A computer algorithm had to be developed to control the cooling-water temperature.

It is difficult to describe the exact conditions in a cooling system during the operation of an engine. The water pump is connected to the engine shaft and therefore the coolant flow changes with the engine speed. Some changes had to be made to build in the heat exchanger. Consequently, some restrictions and angles were introduced to the cooling system of the engine. To reduce the vibrations some pipes were made from rubber. Considering everything mentioned above and the fact that neither the ventila, povzamemo, da želene temperature hladilne vode ne moremo zagotoviti z načelom krmiljenja (določitev ustreznega odprtja glede na vstopne parametre). Zato smo se odločili za načelo krmiljenja s povratno zvezo. V tem primeru je bilo treba izbrati mesto, na katerem smo merili primerjalno temperaturo. V primeru, da je temperatura v primerjalni točki različna od želene, računalnik sproži postopek, ki ustrezno prilagodi odprtje mešalnega ventila. Za primerjalno mesto je mogoče izbrati katerokoli mesto v hladilnem krogu motorja za mešalnim ventilom. V našem primeru smo poskusili z obema skrajnima točkama (4 in 6 na sliki 1). Izkazalo se je, da je bolj ugodna točka številka 4, ker potuje voda od mešalnega ventila do točke manj časa (krajši mrtvi čas), pa tudi mešanje je dovolj dobro, da je izmerjena temperatura reprezentativna.

2.1 Strojna oprema

Računalniški sistem za zbiranje podatkov, ki ga uporabljamo v laboratoriju, je sestavljen iz večfunkcijske kartice AT-MIO-16E-2 in sistema za pripravo signalov. Tako za zbiranje analognih napetostnih signalov uporabljamo modul SCXI-1140, za zbiranje termoelektričnih napetosti modul SCXI-1102, imamo pa tudi modul SCXI-1124, ki omogoča dostop do analognih izhodnih signalov, in pa modul SCXI-1161 , ki vsebuje 8 relejev in omogoča preklapljanje napetosti. Večfunkcijska kartica je nameščena v osebnem računalniku, moduli pa v okrovu SCXI-1000. Vsa omenjena oprema je izdelek National Instruments. Odločili smo se, da bomo zbirali podatke o delovanju motorja (signale za vrtilno frekvenco in navor smo odvzeli iz motorske zavore in dovedli na modul SCXI-1140), temperaturah (termoelementi so vezani na SCXI-1102), krmiljenje odprtja mešalnega ventila pa bomo izvedli z releji v modulu SCXI-1161.

2.2 Programska oprema

Za pisanje programov uporabljamo programski paket LabVIEW, ki je prav tako izdelek podjetja National Instruments. Programiranje se izvaja grafično, kar omogoča dobro preglednost programov. Delovanje programa je predstavljeno na sliki 2.

Celoten program, se odvija v pogojni zanki. Najprej se določi trenutni čas iteracije. Nato se zberejo napetosti na termoelementih in spremenijo v temperaturo. Algoritem za spremembo napetosti v temperaturo je vgrajen v programu LabVIEW, prav tako pa oprema omogoča tudi merjenje in kompenzacijo temperature hladnega člena. Izračuna se razlika med dejansko in želeno temperaturo na primerjalnem mestu. Glede na predznak razlike se preklopi rele R1 (odpiranje ali zapiranje mešalnega ventila). Glede na absolutno vrednost razlike pa se izračuna potreben čas vrtenja mešalnega ventila:

control valve nor the actuator allows us to know the exact position of the valve there was only one way to solve the problem; we had to develop a temperature feedback control system. We chose a reference point, and if the actual reference temperature was too high or too low then the computer-based algorithm made an adjustment to the control-valve opening. Every measuring point downstream of the control valve could be selected as a reference point. We experimented with the points directly after the control valve and just before the engine (points 4 and 6 in Figure 1). Point 4 gave us better results because the water takes less time to reach this point (shorter time delay).

2.1 Hardware

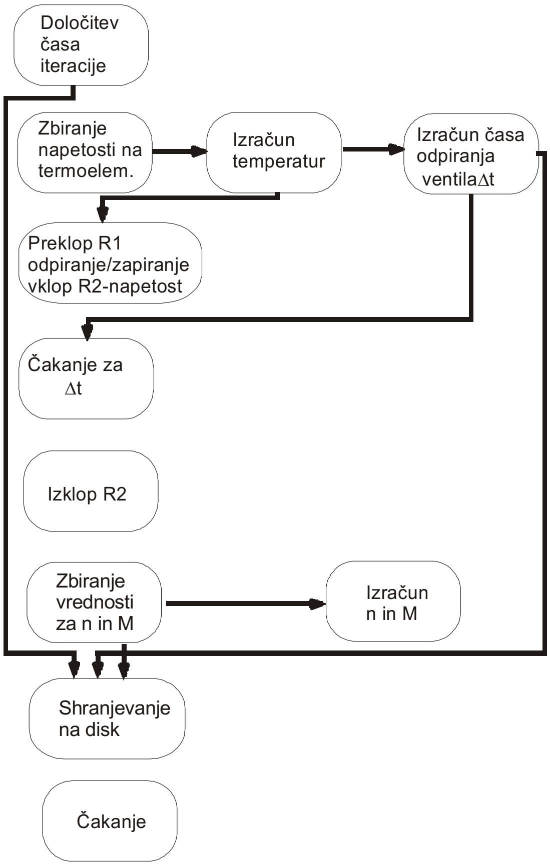
The computer-based data-acquisition system used in our laboratory consists of a multifunction Daq card AT-MIO-16E-2 and signal-conditioning modules. For the acquisition of analog voltage signals we use a SCXI-1140, the thermocouples are connected to a SCXI-1102. SCXI-1124 (access to analog output signals) and SCXI-1161 (8 power relays) modules are also placed in a SCXI-1000 chassis and can be used for control purposes. The equipment is produced by National Instruments. We decided to measure engine speed, torque (voltage signals were taken from engine dynamometer and connected to the SCXI-1140) and temperatures (thermocouples were connected to the SCXI-1102). Relays in the SCXI-1161 were used for the control valve.

2.2 Software

An algorithm was developed graphically using the LabVIEW Program, which gives us good transparency of programming. The flow-chart is presented in Figure 2.

The whole program is placed in a while loop. First, the running time of an iteration is determined, after this the thermocouple voltages are acquired and converted to temperature. The conversion algorithm is included in LabVIEW. The cold-junction compensation is also supported in the software and hardware. The difference between the actual temperature and the set-point value is calculated, if the actual temperature is higher than desired then R1 selects opening of the control valve and vice versa. According to the absolute value of the difference, the time of the power supply and consequently the rotation time of the control valve is calculated :

$$\Delta t = k \cdot \left| T_{dej} - T_{ciljni} \right| \qquad (1),$$



Sl. 2. *Delovanje programa*

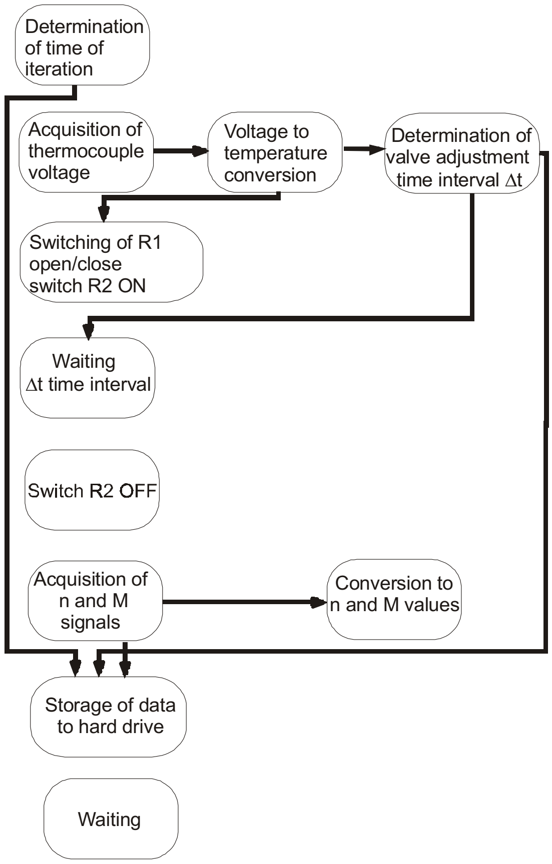


Fig. 2. *Flow-chart of a program*

pri čemer je *k* koeficient, ki ga je mogoče spreminjati, najboljše rezultate za obravnavani motor pa dobimo pri vrednosti za k med 0,15 in 0,2.

Sledi vklop releja R2 za napajanje servomotorja. Po preteku časa ⊗*t* se rele R2 izklopi, s čimer se doseže želena sprememba odprtja mešalnega ventila. Ker potrebuje voda določen čas, da pripotuje iz mešalnega ventila do primerjalnega mesta, je treba ta čas upoštevati tudi v programu. Zato se čas po končani spremembi odprtja mešalnega ventila porabi za zbiranje podatkov o delovanju motorja in shranjevanje podatkov o motorju in temperaturah na disk. V primeru, da pride do nestabilnosti krmiljenja, pa je mogoče izvesti še dodatno čakanje na koncu iteracije, kar izboljša ponovljivost, v tem času pa je mogoče sistem uporabiti za zbiranje dodatnih parametrov o delovanju motorja (poteki tlakov v polnilnem kanalu, valju, signali iz elektronike motorja itn.)

Uporabljena oprema za zbiranje podatkov omogoča zbiranje do 32 temperaturnih signalov. V našem primeru smo temperaturo merili v 13 točkah.

3 REZULTATI

Delovanje sistema smo preskusili na motorju Renault J7T 706. Osnovni podatki o motorju so podani v preglednici 1.

Pri tem smo nastavili ročico za plin v določeno lego in pri tej legi na motorski zavori

where *k* is a parameter which can be adjusted. The best results were achieved with values of *k* between 0.15 and 0.2.

Relay R2 switches the power on. After the calculated time interval the power is switched off and an adjustment to the control-valve position is completed. Because it takes some time for the water to reach the measuring point, this time must be considered in the control algorithm. We also used this time for acquiring the engine torque and speed as well as storage of data to the disk. If the control becomes unstable or other signals have to be acquired it is possible to increase the waiting time and use it for acquiring other parameters (pressures in the intake manifold, valve, signals from engine electronics, etc.).

The equipment can acquire up to 32 thermocouple signals. In our case 13 thermocouples were used.

3 RESULTS

The system was tested on Renault J7T 706 engine, the engine characteristics are summarised in Table 1.

The throttle valve was fixed in a certain position and the engine speed was set to maximum.

Preglednica 1. *Podatki o motorju Renault J7T 706*
Table 1. *Renault J7T 706 engine specifications*

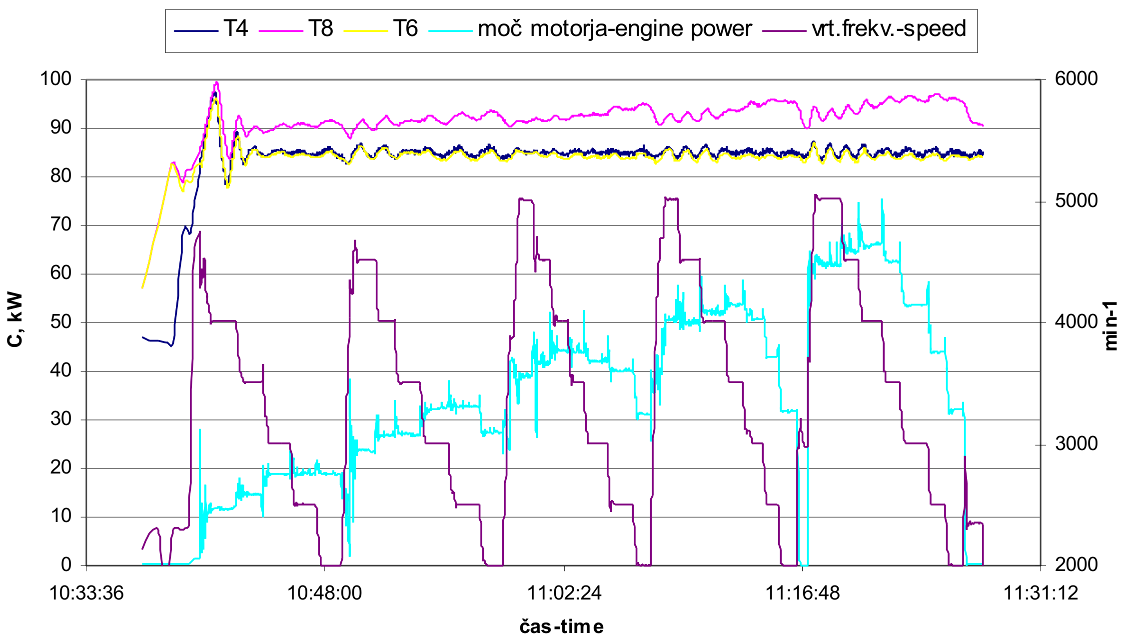
število valjev number of cylinders	4
največja moč rated power	75 kW
prostornina displacement	2200 ccm
gorivo fuel	bencin/petrol

spreminjali nastavljeno vrtilno frekvenco motorja v mejah od prostega teka motorja do vrtilne frekvence motorja 2000 min^{-1} s korakom po 500 min^{-1}. Ko smo dosegli vrtilno frekvenco 2000 min^{-1}, smo nekoliko dodali plin in ponovili postopek. Pri tem smo dosegli največjo moč motorja 65 kW in največjo vrtilno frekvenco motorja 5000 min^{-1}. Tako smo popisali zelo široko delovno območje, v katerem so se tudi močno spreminjale razmere v hladilnem sistemu motorja, tako zaradi sprememb toplotnega toka, ki s hlajenjem prehaja na hladilno vodo (sorazmerno moči motorja), kakor tudi zaradi spremembe pretoka (sorazmerno vrtilni frekvenci motorja). Potek temperatur v hladilnem sistemu in trenutna moč motorja sta prikazana na sliki 3. Konice poteka moči so posledica trenutnega povečanja obremenitve na zavori, do katerih pride pri spremembi vrtilne frekvence motorja.

Razvidno je, da sistem omogoča dobro ujemanje dejanske temperature na primerjalnem mestu z nastavljeno (85°C) ne glede na spremembo moči motorja in s tem povezano spremembo temperature vode na izstopu iz motorja, kakor tudi glede na spremembe

By changing the dynamometer load torque, the engine speed was reduced in 500-rpm steps until it reached 2000 rpm. The throttle valve was fixed in another position and the procedure was repeated. During the testing the engine power varied from 65 kW to 0 kW and the speed varied between 5000 rpm and 2000 rpm. The temperature-control algorithm was tested over a wide working range of the engine. During testing, parameters like heat flux (proportional to engine power) and cooling-water flow (proportional to engine speed) changed significantly. Temperatures of the cooling water at different positions in the cooling system are presented in Figure 3 together with engine power and speed. Peeks in the curve representing the engine power were caused by a sudden increase in the torque when the engine speed was reduced.

From Figure 3 we can make some more conclusions. The system gave us good agreement between the actual and desired (85°C) temperatures at the reference position, regardless of the engine speed and the power changes. The increase in the



Sl. 3. *Potek temperature hladilne vode in moči motorja med preskušanjem*
Fig. 3. *Temperatures in the cooling system and engine power during testing*

masnega toka hladilne vode, ki so posledica spremembe vrtilne frekvence motorja. Zvišanje temperatur na začetku testiranja je posledica popolnega zaprtja mešalnega ventila na začetku testiranja. V trenutku, ko termostatski ventil spusti vodo iz motorja v hladilni sistem, pride do skokovite spremembe temperature hladilne vode in krmiljenje potrebuje nekaj časa, da ustrezno prilagodi odprtje mešalnega ventila. Ko se razmere ustalijo, je krmiljenje dovolj hitro in dovolj stabilno, da zadrži temperaturo hladilne vode znotraj območja ±2 °C od želene temperature ne glede na spremembo moči motorja in njegove vrtilne frekvence. Razlika med temperaturama T4 (na vstopu v hladilnik) in T6 (na vstopu v motor) je približno 1°C, iz česar je mogoče sklepati o toplotnem toku hlajenja pri izklopljenem ventilatorju.

Zapisovanje temperatur in podatkov o delovanju motorja poteka avtomatično, kar razbremeni osebje, ki izvaja preskušanje. Sistem se da z manjšimi spremembami (faktor k v enačbi (1)) uporabiti pri testiranju drugih vodno hlajenih motorjev.

temperatures at the beginning of the test is the result of a closed control valve. At the moment when water is released from the engine to the cooling system (opening of the thermostatic valve), the temperatures in the cooling system change suddenly and the system needs some time to react. After stabilisation, the system is capable of maintaining the temperature to within ± 2°C, regardless of engine power and speed changes. The difference between the temperatures T4 and T6 is approximately 1 °C, from which we can estimate the cooling power of the car radiator with its fan switched off.

Using this procedure we have acquired the temperatures, the engine speed and the power automatically. This is useful because the number of staff performing the test can be reduced. The system was (with some modifications to parameter k) successfully used for testing other water-cooled engines as well.

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