ISSN 1454 - 8003
Proceedings of 2017 International Conference on Hydraulics and Pneumatics - HERVEX
November 8-10, Băile Govora, Romania

AUTOMATED HYDRAULIC OIL COOLING SYSTEM DRIVEN BY A VARIABLE SPEED HYDRAULIC MOTOR

Iulian-Claudiu DUȚU[1], Radu-Iulian RĂDOI[2]

[1] University Politehnica of Bucharest, Romania, iulian_claudiu.dutu@upb.ro

[2] Hydraulics and Pneumatics Research Institute, Bucharest, Romania, radoi.ihp@fluidas.ro

Abstract: *Oil cooling systems are used widely in hydraulic systems, mainly to maintain working fluid's (oil) temperature within a given range, where its flowing parameters have small variations. It is a well-known fact that hydraulic oil parameters, such as viscosity and pressure drop, are dependent to current oil temperature therefore in many cases it must be controlled using automated cooling systems. The authors propose an automated hydraulic oil air cooling system having as main actuator a variable speed rotary hydraulic motor. Cooling capacity must be calculated, using standardized formulae that are to be found in scientific literature, under-sizing always lead to poor temperature balance. Overheating can create favorable conditions for the occurrence of cavitation phenomenon, leading to premature wear or damage of hydraulic equipment. The testing stand that the authors propose is made of an operator console placed on a hydraulic oil tank, a battery of oil filters, hydraulic directional valves, safety valve, electronic temperature to current transducers and the electronic controller module.*

Keywords: *automated system, testing stand, transducers, simulation*

1. Introduction

Hydraulic fluids, also known as hydraulic oil or hydraulic liquid, can be defined as the medium used to transfer power in hydraulic installations or systems. Its physical and chemical characteristics can be measured and give the extent to which system's overall efficiency is appreciated. In energy terms, an automated cooling system is working with the energy that the hydraulic installation / system does not consume when working – also known as lost energy:

$$W_{cooler} = W_{input} - W_{used} \tag{1}$$

Trying to maintain the oil at ideal working temperature is highly desired, having direct positive benefits both on hydraulic system's working life and oil life, reduced maintenance and repair costs, lower system downtime and higher efficiency when oil temperature is somewhere around the ideal working temperature (in practice the oil's temperature is varying in a range of values).

The automated hydraulic oil cooling system, was tested on an general purpose electro-hydraulic testing stand, made of an operator console, an oil tank having an approximate volume of 800 liters, a battery of oil filters, several hydraulic directional valves, a safety valve, electronic temperature to current transducers and the electronic controller module. All will be detailed in the following. The operator console is a rectangular metallic plate, having T-shaped channels on which is mounted, mainly, tested equipment and auxiliary hydraulic valves or electro-mechanical devices.

The paper is presenting the electro-hydraulic diagram of the automated cooling system that the authors propose, several key technical parameters of main components. The system is using an air cooler with a variable speed hydraulic motor.

2. Current state of the art

Hydraulic driven cooling system, with an air fan, are using a variable speed motor is considered to offer significant advantages over classic electric or belt-driven solutions, such as energy savings, accurate and variable speed control of the fan, extended working life and the possibility to find integrated cooling systems on the market.

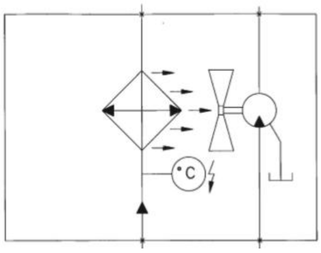


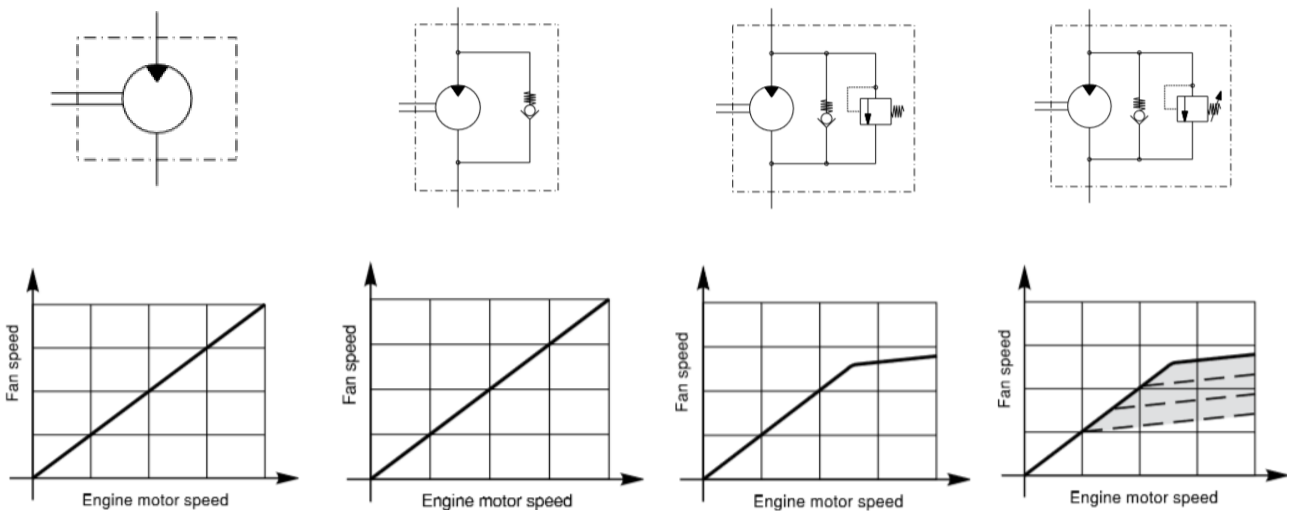
Fig. 1. General connection for an air hydraulic oil cooler with hydraulic rotary motor

Mainly, there are known three technical solutions for hydraulic oil cooling using:

a. *fixed ratio* hydraulic rotary motor, the case which the cooling system's fan has only one rotational speed, proportional with the drive motor's (electric, hydraulic) speed,

Fig. 2. Fixed ratio hydraulic motor

The hydraulic motor can be provided with auxiliary hydraulic equipment, such as pressure relief valves or anti-cavitation valves, but it also can operate in stand-alone configuration, without using these equipment.



a. stand-alone | b. with anti-cavitation valve | c. with pressure relief valve (fixed) and anti-cavitation | d. with pressure relief valve (adjustable) and anti-cavitation

Fig. 3. Different operating modes for fixed ratio hydraulic motors

ISSN 1454 - 8003
Proceedings of 2017 International Conference on Hydraulics and Pneumatics - HERVEX
November 8-10, Băile Govora, Romania

Basically, in every one of the four operation modes given above, the hydraulic motor performs the same function, but there are few disparities: in Fig. 3.a, the construction is simple and robust, therefore is expected to be a cost effective solution; in Fig. 3.b, the hydraulic motor is protected, but in the same time it can attain higher rotary speeds then the case before; in Fig. 3.c, the motor has the same benefits as in Fig. 3.b, but a long-life operation if expected than the cases before. The recommended configuration when using a fixed ratio hydraulic motor is the one given in Fig. 3.d, where besides higher rotary speeds, motor protection and larger fan size, the system can be optimized due to its adjustability. Analyzing the associated functional curves, *fan speed vs. engine motor speed*, it can be easily differentiate the functional characteristics in each one of the four connection modes. Best operation case is given in Fig. 3.d, but it is also the most expensive one.

b. *two speed* hydraulic rotary motor, when the cooling system's fan can rotate at two different speeds, therefore the cooling system can operate in two modes: normal cooling mode and turbo cooling mode,

Fig. 4. Two speed hydraulic motor

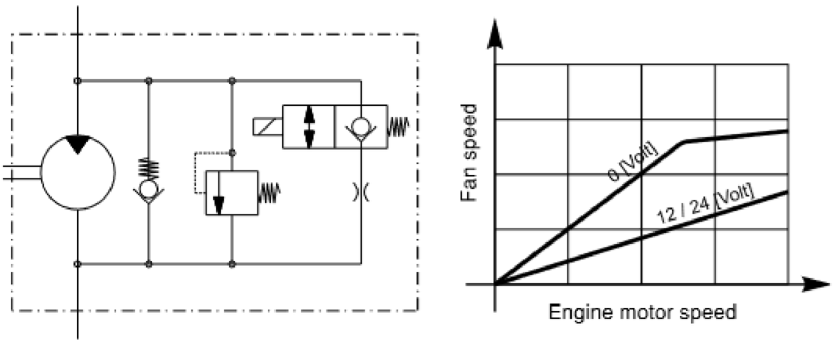


Fig. 5. Two speed hydraulic motor with piloted bypass valve, pressure relief valve (fixed) and anti-cavitation

Technical advantages of using such a configuration are: high operation speeds, hydraulic motor protection against pressure peaks, large fan sizes and the electronic command for two operating cooling speeds. Usually, the electromagnet of the piloted bypass valve operates on 12VDC for normal cooling and 24VDC for turbo cooling. It must be noted that any other intermediate rotary fan speeds are not possible in this configuration, as seen in the characteristic curve in Fig. 5.

c. *variable speed* hydraulic rotary motor, having the benefit of that the operator can change the direction of rotation when needed. In this case, the rotational speed of the fan driving axle is independent of the driving engine speed, but needs, at least, an electronic module to control the speed variation and direction change.

Fig. 6. Variable speed hydraulic motor

In the case of using a variable speed hydraulic motor, the fan speed is independent of drive engine speed. It is the most expensive solution of all presented above, but acquisition costs are not always the only choosing criteria.

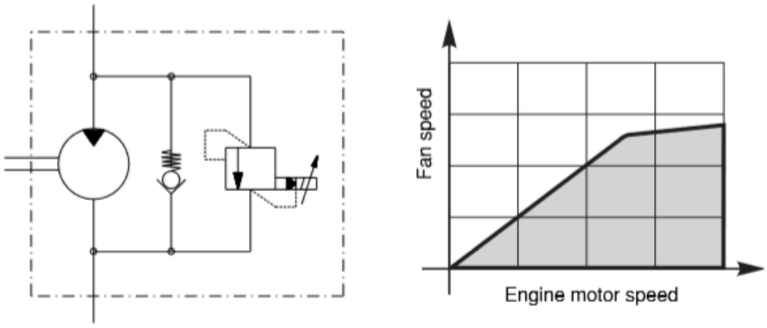


Fig. 7. Variable speed hydraulic motor with proportional relief and anti-cavitation valves

Besides the high speed operation, long operating life and motor protection, there is attained a proportionally precise control of coolant temperature, while in a case of a control module failure, the fan will be rotating at its maximum speed.

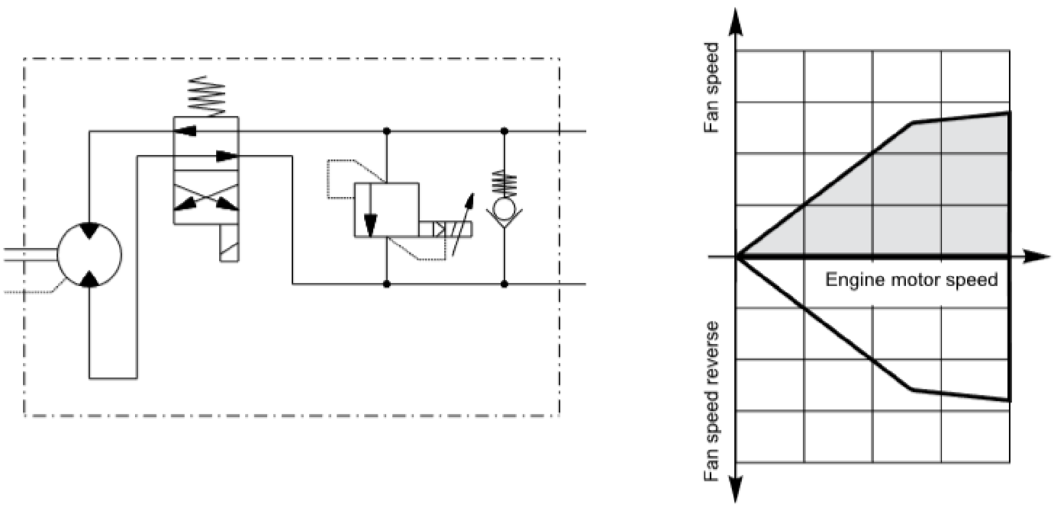


Fig. 8. Variable speed hydraulic motor with
4/2 reverse valve, proportional relief valve and anti-cavitation valve

The most efficient operating mode of an air oil cooler is to use a variable speed hydraulic motor connected using the diagram given in Fig. 8, which is also provided with the possibility to change the direction of rotation - it is used a 4/2 electric valve. In addition to the features presented in the previous case, reversible operation of the cooling fan, allow the system to perform an "auto-cleaning" of the radiator element. The speed variation is current controlled using a specialized electronic module, which generates a PWM signal of which frequency is proportional to hydraulic motor speed, with an adjustable dither signal. The electronic module controls the hydraulic motor rotational speed by simply regulating the current that flows through the electromagnet of the proportional relief valve.

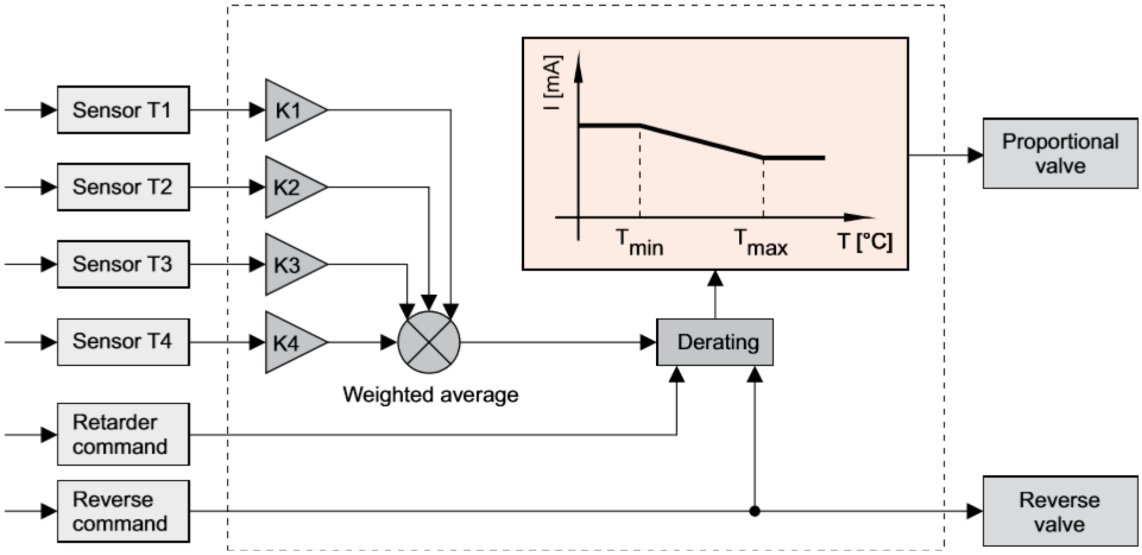


Fig. 9. Schematic of an electronic control module used in a variable speed fan drive system with variable speed hydraulic rotary motor

The schematic given in Fig.9 has a number of four temperature sensor inputs, for each one it can be set the minimum and maximum working (control) temperatures and a weight coefficient in accordance with so-called "thermal importance" in the control loop. Depending on the proportional valve type, the minimum and maximum control currents can be set. From Fig. 9 it can be seen that the electronic control module calculates the proportional valve drive current using a weighted average of temperatures measured in different point of the hydraulic installation. The electronic control module has a retarder function allowing the operator to increase or decrease the hydraulic motor speed by simply changing the control current of the hydraulic proportional valve. There is also available a reverse function used only for reversible hydraulic motors in the reverse valve configuration, thus allowing changing the direction of rotation used for cleaning cycles of radiators.

Fig. 10. Air hydraulic oil cooler using a hydraulic rotary motor (LHC, OA-Technik GmbH)

3. System description

Given the above, the authors propose an electro-hydraulic diagram of the automated oil cooling system, using a variable speed hydraulic motor.

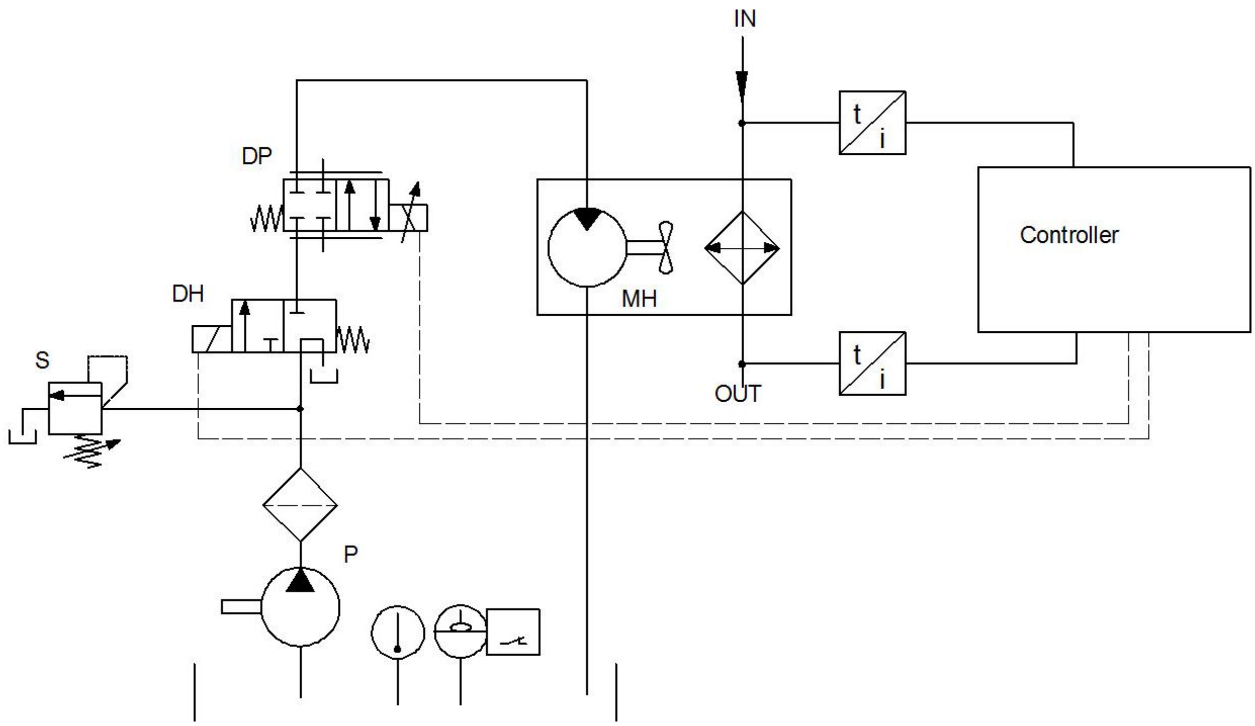


Fig. 11. Schematic diagram of the automated cooling system

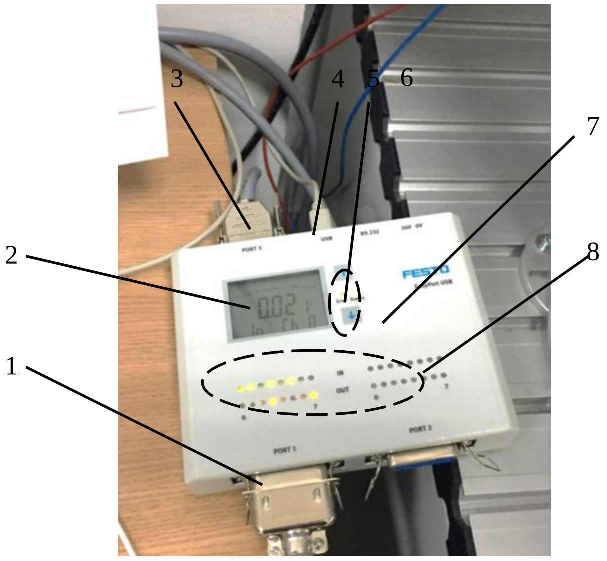
The diagram of the automated hydraulic oil cooling system that the authors propose is using: a proportional 4/2 directional valve *DP*, a 3/2 directional valve *DH*, a pressure relief (adjustable) valve *S*, a hydraulic pumping module with electronic level display and mechanical temperature indicator, the air oil cooling with variable speed hydraulic motor *MH*, a hydraulic filter battery, two electronic fluid (hydraulic oil) temperature-to-current transducers and the electronic control module. The electronic fluid temperature transducers are using Pt100 thermocouples, having the operating temperature range of [-50°C … +150°C] and an output voltage of 0…10V, with signal converter. When the cooling function is not needed, the 3/2 directional valve *DH* is acting as a hydraulic switch, decoupling the hydraulic cooling system from the main installation.

3.1. Main components

Referring to the electronic control module, it can be materialized using a dedicated controller based on a RISC microcontroller, a programmable logic controller (PLC) or a personal computer with a data acquisition board. In any case, the control module must be programmed using proper software environment. The controller described in this paper was made using the third option from the above: PC and DAQ board. Presented configuration is using a 16-bit FESTO EasyPort DAQ, as seen in Fig. 12.a, with analog and digital connection boards, Fig. 12.b. This DAQ board is interfacing the cooling system’s temperature transducers on two analog inputs and two DC electromagnets, one connected on a digital output (0/24VDC) for directional valve *DH*, while the other one, for *DP* proportional directional valve, is connected on an analog output, generating proportional command. The DAQ board communicates with the PC using a USB connection standard. Also, the DAQ board can supply regulated 24VDC power to the temperature transducers and other electric consumers, max. 1A. When choosing the data acquisition card, the authors have considered the following criteria:

- maximum *sampling rate*, which is the measure of the speed at which an analog input of the acquisition board is scanned and updated, in order to acquire a numerical value of the analog signal present on the input. If the sampling rate is incorrectly selected, the acquired signal will not be the same as the original signal;

- the *resolution* is represented by the number of divisions in which the input signal variation range is divided;
- number of *analog inputs*, closely related to the number of signals that can be purchased simultaneously;
- number of *analog outputs* used by the PC to generate analog signals send to the testing stand.



a. DAQ board

b. analog and digital connectors

Fig. 12. DAQ board and its connectors

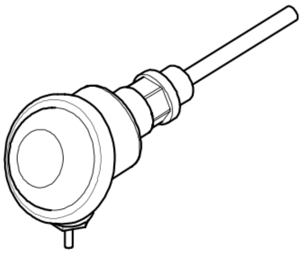
In Fig. 12.a, are given: 1. digital signal cable; 2. data acquisition board display; 3. analog signal cable; 4. USB data cable; 5. configuration buttons and status LEDs; 6. power supply (24 VDC).

The EasyPort USB DAQ board is equipped with two configuration buttons and two LEDs (green and red) that optically signal the state of the board as follows:

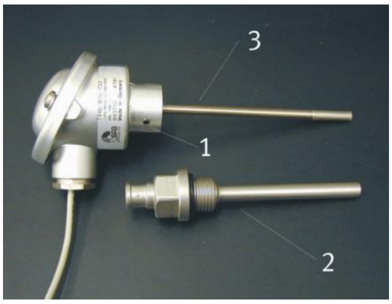
- red LED flashes when a short circuit is detected at one of its outputs. In this case, EasyPort USB outputs are disabled as a protective measure. This LED illuminates briefly when the DAQ board is electrically powered;
- green LED can indicate optically the following states of the DAQ board:
  - an intermittent illumination with a frequency of approximately 1 Hz immediately after the electric powering, meaning that the acquisition card has not started communicating with the computer to which it is connected;
  - a fast flashing, meaning that the acquisition card was recognized and connected to the computer without any errors.

The LCD display of the DAQ board is used to inform the operator about voltage levels from a selected analogue input / output, in numerical form and in the form of a bar-graph, the length of which is proportional to the value of the input. The LCD display also shows the number of input / output displayed and the type of signal: input or output. Two groups of 16 LEDs, Fig. 12, are used on the DAQ board indicating the current state of the digital inputs and outputs. The green LEDs indicate the status of the digital inputs as: LED off – zero (low) input value; LED illuminated – high input value. The yellow LEDs indicate the state of the digital outputs, having the same optical significance as the inputs. The two buttons on the front panel of the DAQ board are used to select

the input or output number and the unit of measure (V, bar, PSI, MPa, l / min, °C) in which the value on the LCD display is displayed.
The transducers of the experimental stand perform the conversion of a physical measure (temperature) into a proportional electrical signal (voltage).



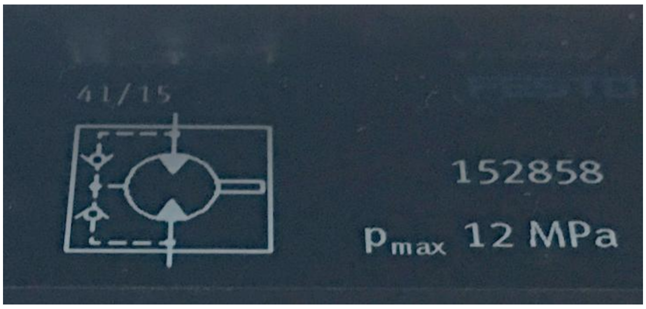
a. schematic drawing



b. physical model

Fig. 13. Temperature transducer, Pt100

Another main component of the automated oil cooling system is the variable speed hydraulic motor, OMM8 type, manufactured by Danfoss, shown in Fig. 14. Few important technical characteristics of the motor are: operating pressure 60 bar, maximum permissible pressure 120 bar, maximum permissible pressure in the return line 50 bar, displacement 8,2cm^3/ rot, 0…10 l/min, 0…1220 rpm, low leakage.



a. motor schematic

b. motor mounted on testing stand

Fig. 14. Variable speed hydraulic motor

The hydraulic motor speed is controlled by the *DP* proportional directional valve, which is driven by the electronic controller.

3.2. Virtual instrument - controller

The electronic controller module, as stated before, is based on a PC – DAQ board system, using a VI, virtual instrument, developed in LabView software environment. Instrument (user) panel of the VI is shown in Fig. 15, where can be seen several displays and control instruments. The VI has an activation switch (ON/OFF) which starts or stops temperature control. There is placed on the instrument panel a display for the rotational speed of the hydraulic motor, a green LED indicator that is lighted in light or dark green according to the ON or OFF state of the *DH* directional valve (bypass valve), two displays calibrated from 0 to 100ºC that display in real time the current temperature value at the in and out connectors of the air hydraulic oil cooler. The most important two controls on the instrument panel are the *PID output [%]* and *PID gains*, the VI uses a standard software proportional-integrative-derivative controller (PID) to calculate the command for the electromagnet of the proportional hydraulic directional valve *DP* and displays it. PID controller output is shown in percent, physically corresponding to electric current values applied to the proportional electromagnet of *DP*, in range from 200 to 800mA.

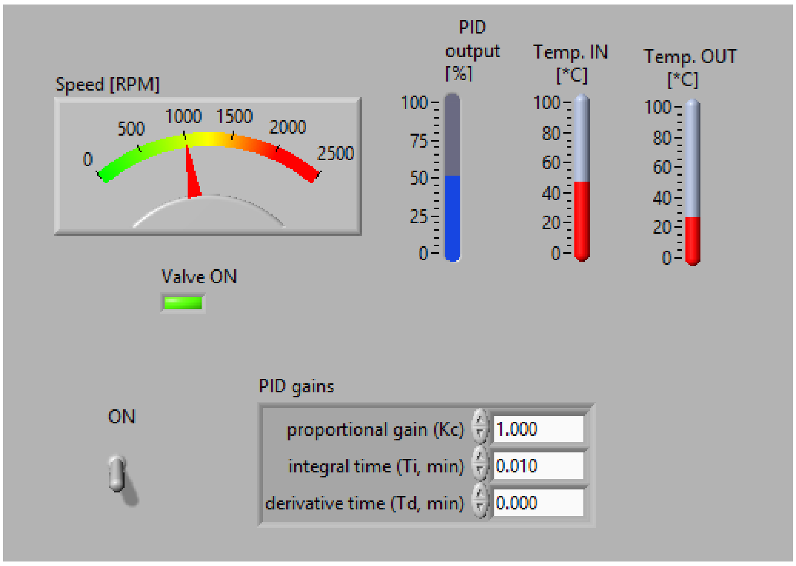


Fig. 15. Virtual instrument for automated control of the oil cooler

4. Conclusions

Automated hydraulic oil cooling systems are necessary extensions of any modern hydraulic testing stand, especially when performing endurance tests on classic or proportional hydraulic equipment. Proper fluid (hydraulic oil) temperature control is a key factor for obtaining accurate results when acquiring data for plotting characteristic curves of hydraulic equipment. Another important aspect of using an automated oil cooling system is reducing premature wear of the hydraulic equipment, implying – on long term – lower maintenance and service costs. Automated systems reduce the percent of human operator intervention on tasks that have a low level of importance in hydraulic systems and installations, taking over monitoring and control task but notifying the operator only in potential dangerous situations.

Acknowledgment

This work has been funded by Executive Unit for Financing Higher Education, Research, Development and Innovation - UEFISCDI, under PNCDI III - Programme 2, Subprogramme 2.1 – Transfer project to the economic operator (PTE-2016), Submission code PN-III-P2-2.1-PTE-2016-0077, Financial agreement no. 11PTE/2016, project title: High energy efficiency (HEE) electro hydraulic equipment (EHE) for multifunction vehicles (MFV), project acronym ECHIPEFEN, Project main domain: 3. Energy, Environment and Climate Change, Subdomain: 3.1. Energy.

References

[1] L. Szabo, “Modelarea sistemelor electromecanice”, U.T.Cluj;
[2] T.Tudorache, “Medii de calcul în inginerie electrică – MATLAB”;
[3] C. Ionete, D. Selişteanu, A. Petrişor, “Proiectarea sistemică asistată de calculator în MATLAB, Reprografia Universităţii din Craiova, 1995;
[4] N.E. Leonard, W.S. Levine, “Using MATLAB to analyze and design Control Systems”, Addison-Wesley Publ., SUA, 1995;
[5] P. Marchand, “Graphics and GUIs with MATLAB”, CRC Press, SUA, 1999;

[6] Fl. Grofu, "Sistem numeric pentru monitorizarea nivelului, Universitatea „Constantin Brâncuşi" din Târgu-Jiu Asist.ing. Cercel Constantin, Universitatea „Constantin Brâncuşi" din Târgu-Jiu, Analele Universităţii „Constantin Brâncuşi" din Târgu Jiu, Seria Inginerie, No. 3/2012, pp. 125-135;
[7] C. Oprea, Cr. Barz, "Tehnica reglării automate", Tipografia Universităţii de Nord, Baia Mare, 2000;
[8] A.M. Duinea, "Informatica de proces – notițe de curs", Universitatea din Craiova, 2006;
[9] A.S. Băieșu, "Tehnica reglării automate", Editura MatrixRom, ISBN:978-973-755-815-2, 2012;
[10] N.E. Leonard, W.S. Levine , "Using MATLAB to analyze and design Control Systems", Addison-Wesley Publ., SUA, 1995;
[11] *** CASAPPA-Fluid Power Design, "Electro-hydraulic fan drive system", document ID: FD 04 T A, 04 February, 2014, pp.1–38, http://www.casappa.com;
[12] Pius Emmenegger, "LHC, Air Oil Coolers with Hydraulic Motor for Mobile and Industrial Use", 01 March, 2015, pp. 1–7, http://www.olaer.ch;
[13] ***, http://www.festo.ro;
[14] ***, DVD-ROM,"FluidLab PA closed loop, Documentation", Festo Didactic, 07/2015.