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RESULTS ON THE RESEARCH OF THE INFRARED THERMOGRAPHY METHOD APPLIED TO THE HYDRAULIC SYSTEMS DIAGNOSIS

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Abstract: *The maintenance is an important activity, absolutely necessary for the proper operation of any kind of technical system, even for the hydraulic drive systems. Condition-based preventive maintenace (or predictive maintenance) is more than to prevent maintenance because it continuoslly evaluates the state of technical performances of a system. One of the most well-known predictive methods is the infrared thermography. This paper presents the results of an experimental research on a gear pump, in order to demonstrate the advantages of using the infrared thermography method in predictive maintenance of the pump. There are simulated different operation modes of the gear pump by changing the work conditions in the hydraulic drive test system. Specific thermograms are obtained for each operation mode. Observations regarding the measurement errors and the application limits of infrared thermography are made, too.*

Keywords*: Maintenance, predictive maintenance, infrared thermography, hydrostatic pumps, hydraulic drive systems*

1. Introduction

Maintenance is regarded as an important factor in product and service quality and it can be considered a system "viewed as an integrated input-output model" which can be planned, organized, monitored and controlled, [1]. In Figure 1 the input-output maintenance system is shown. In the scientific literature regarding on he maintenance and maintenance management three maintenance strategies are underlined: the corrective (or breakdown) maintenance, time-based (or use-based) preventive maintenance and condition-based preventive maintenance. Other maintenance strategies are: opportunity maintenance, fault finding, design modification, overhaul, replacement, reliability-centred maintenance, total productive maintenance. All these strategies or policies depend on the relationships between maintenance system and organization objectives, [1].
Corrective maintenance (noticed as CM) is focused on performing repair after the system or component failure occurred.
Time-based preventive maintenance, or simple preventive maintenance and noticed as PM, is a planned maintenance performed to prevent and fix problems before failure occurs.
Condition-based preventive maintenance (CBM) is based on monitoring and collecting information concerning the condition of the equipment to prevent unexpected failures and determine optimal maintenance schedules, [2]. Condition-based maintenance is a form of predictive maintenance strategy and is more than a simple PM because the system's reliability indicators are improved and the cost of maintenance is less. The time between two stops is shorter in CBM than in PM. Condition-based maintenance is applied to a sub-assembly, a component or a machine system. Over time, all data obtained from the monitoring parameters according to predictive maintenance program (or CBM) are studied, processed, and compared to the existing data. The statistical analyse will allowed to predict the periodicity of the future maintenance program and to optimize it, too. The most common predictive maintenance methods used in hydraulic systems, are: vibration analysis, oil analysis, infrared thermography and ultrasound control, Fig. 2.
It is not necessary to use all methods in the monitoring the parameters of the hydraulic system within predictive maintenance program. In the references literature, oil analysis, infrared thermography and vibration analysis (or ultrasound control) are recommended, [2].

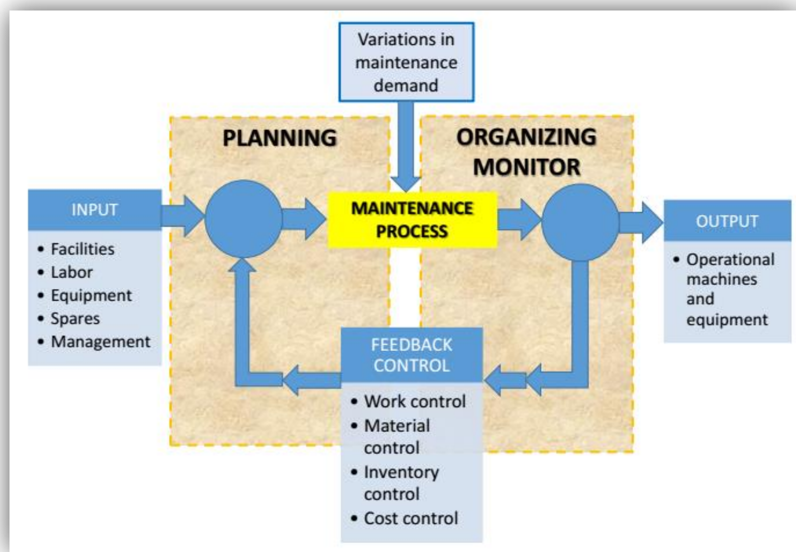

Fig. 1. Maintenance system as input-output model, [1]

Fig. 2. Condition-based maintenance monitoring methods

Starting from these considerations, the authors of the paper present new experimental researches, in continuation of those started at INOE 2000-IHP in 2016, demonstrating the utility and efficiency of using the infrared thermography method in the predictive study of the hydraulic actuation systems operating behaviour, [3].

2. Experimental test rig

In order to achieve the research objective, a testing rig was conceived, designed and physically realized at INOE 2000-IHP Bucharest, to allow the demonstration of the usefulness and the efficiency of the infrared thermography method, using in the behavioral prediction of hydrostatic drive systems. The hydraulic diagram of the test bench is shown in Figure 3.
The test rig is used to test a Vivoil hydraulic gear pump, model XV-2P D / C, having a geometric volume of 9 cm^3/rev (see Fig. 4) used in hydraulic drive systems. The test consists in the simulation of various operating modes, i.e. the operation at different pressure stages, as well as the gradual change of the pump suction conditions, after a suitable procedure.

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The hydraulic components of the test rig are: a hydraulic oil tank (T) fitted with a filling and ventilation filter (FAF) and a return filter (RF). A three-phase electric motor (EM) is mounted on the oil tank cover, which, via a coupling (C), drives the hydrostatic pump (HP) to be tested. The pump (HP) sucks the oil out of the tank, a valve (V), a non-return valve (NRV) being mounted on the suction pipe to maintain full-oil the suction circuit, and a throttle (ST) by can modify by throttling the suction circuit of the pump, to change the suction conditions. Throttling of the suction pipe section will lead to increased operating temperature, a phenomenon that will be sensed, measured and recorded by a FLIR infrared thermal imaging camera. The hydrostatic pump (HP) discharge the oil under the pressure indicated by the pressure gauge (G) and is adjusted to the pressure return valve (PRV) by means of a throttle (RT) mounted on the pump discharge, which allows the required pressure steps to be achieved, the oil being returned to the tank through a return filter (RF).

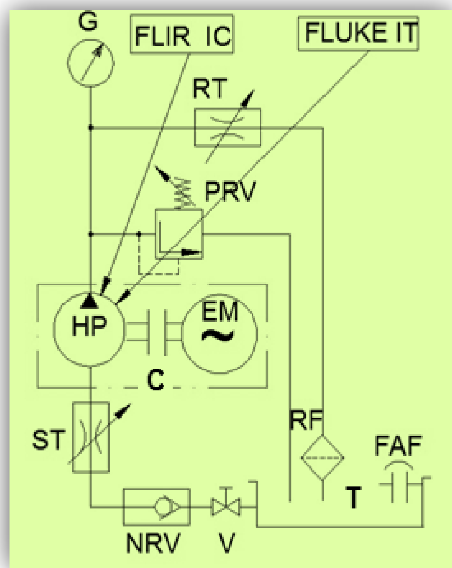

Fig. 3. Hydraulic scheme

Fig. 4. Hydraulic gear pump, Vivoil brand– Italy, [4]

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During the experiments, the measured and monitored parameters were: ambient temperature, oil temperature, working pressure read on the pressure gauge (G), noise in installation read with Smart-Sensor (SSM), but particularly, the pump temperature, measured with 3 devices, namely: with a contact thermometer (CT), placed directly on the pump, with a FLUKE IT infrared thermometer, and with a FLIR IC infrared thermal imaging camera. To measure the temperature at the interest points (pump, tank, oil), the stand was provided with:

- contact thermometer (CT), Checktemp 4 by Hanna brand, to measure the temperature directly on the pump housing (see Fig. 5);

- infrared thermometer (FLUKE IT) for non-contact temperature measurement at the three points of interest (see Fig. 6);
- infrared thermal imaging camera (FLIR IC), required for temperature measuring and recording, at interest points (see Fig. 7);
- Soundmeter (SSM) for noise measurement, Smart Sensor AR 814 brand, (see Fig. 8)

Fig. 5. Contact thermometer Checktemp 4 by Hanna

Fig. 6.FLUKE infrared thermometer

Fig. 7. FLIR infrared thermal imaging camera

Fig. 8. Smart Sensor AR 814 Soundmeter

To highlight the possibility of using the infrared thermography method, to the behavioral prediction of hydrostatic drive systems, some working scenarios were imagined. Thus, under laboratory conditions, different pump operating modes are simulated, leading in an increase of the pump temperature. This is like as the pump is operating with major failures, which lead to the temperature increase, seized through periodic measurements, which allow the early detection of possible failures in the future. In this way major major malfunctions in pumps operation mode can be prevented and important technical and economical decissions regarding the gear pump manufacturing process can be done.
The experiments procedure consists into applying various pressure steps to the hydrostatic pump and for each pressure step, the temperature is measured after regular periodes of time (i.e. 10 min.). Two situation of working are considered: pump operating with the throttle valve (named SITUATION I) and pump opearting without throttle valve (named SITUATION II). The first scenario

is as like the pump is on going to fail because the throttle valve (ST) is on the pump input (Fig. 3.) and cavitation phenomenon can appear when the suction conditions are changed.
The temperature of the pump is measured with three measuring devices: an infrared FLIR thermal imaging camera (FLIR IC, see Fig. 3), an infrared FLUKE thermometer (FLUKE IT, see Fig. 3) and a contact thermometer (CT), placed directly on the pump.
During the experiments were measured the temperatures (with all three types of devices), and the noise for each pressure step in each operating mode.
The main phases of the experiments are as follows:

- setting of the time interval for the measurements, respectively for reading values;
- reading the temperature of the environment, T_{env};
- reading the background noise, A_{env};
- starting the electric motor (EM) to drive the pump;
- adjusting the desired pressure step by actuating the pressure circuit throttle (RT);
- changing the suction conditions of the pump by actuating the throttle mounted on the suction pump circuit (ST);
- monitoring the pump operation temperature and the noise for each setting time interval;
- stopping the pump when the temperature reaches about 80 °C;
- the resumption of the measurement cycle for another pressure stage and for another section area of the suction throttle valve (RT).

The procedure is the same in each working situations with suction throttle valve (SITUATION I) and without suction throttle valve (SITUATION II). If the pump is working in SITUATION II the suction throttle valve is widely opened.

3. Experimental measurements

The experiments were carried out on three steps of pressure, namely: 50 bar, 75 bar and 100 bar. Following experimental procedure described above, the results of the experimental measurements of temperatures and noise are shown in Table 1 and Table 2. for the case of 75bar pressure step. For the pressure of 50bar and 100bar the results were reported in paper [5].
In Table 1 are presented the results of SITUATION I of working, with suction throttle valve and in Table 2, SITUATION II without the suction throttle valve.
During the experiments were monitoring not only the pump temperature measured on the pump housing (T_{pp}) but also the oil temperature (T_{oil}) and the reservoir temperature (T_{rez}), too.
The temperature measurements were made with all three devices mentioned above: infrared FLIR thermal imaging camera, infrared FLUKE thermometer and a contact thermometer (CT), placed directly on the pump.
The temperature measured with contact thermometer can be considered as a standard temperature.

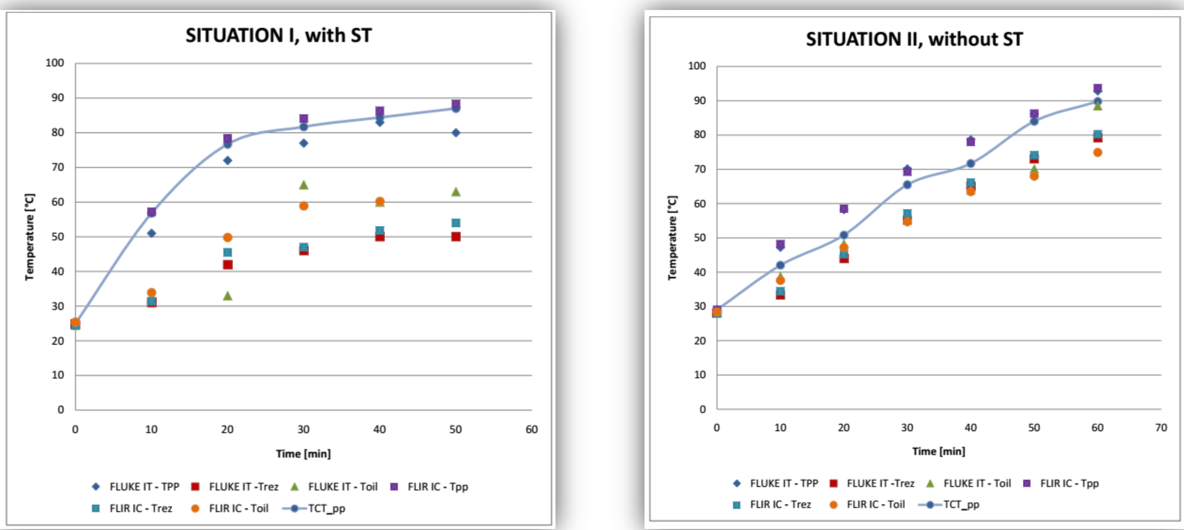
Table 1: Experimental results in SITUATION I, with suction throttle valve ST

Time [min]	**FLUKE IT [°C]**			**FLIR IC [°]**			**CONTACT THERMOMETER CT [°]**	**Noise [dB]**
	T_{pp}	T_{rez}	T_{oil}	T_{pp}	T_{rez}	T_{oil}	T_{CT_pp}	A
0	25	24,7	24,5	25	24,4	25,4	25	44,5
10	51	31	32	57,2	31,4	33,9	56,8	77,9
20	72	42	33	**78,4**	45,5	49,8	76,7	67
30	77	46	65	84,1	47	58,9	81,7	75,7
40	83	50	60	**86,3**	51,8	60,2	84,4	67
50	80	50	63	88,3	54	-	87	

Table 2: Experimental results in SITUATION II, without suction throttle valve ST

Time [min]	FLUKE IT [°C]			FLIR IC [°]			CONTACT THERMOMETER CT [°]	Noise [dB]
	T_{pp}	T_{rez}	T_{oil}	T_{pp}	T_{rez}	T_{oil}	T_{CT_pp}	A
0	29	28	28	29	28	28,4	29	44,5
10	47,2	33,3	38,7	48,2	34,4	37,6	42	75,7
20	58,2	43,9	48,2	**58,5**	45,2	47,2	50,8	75,7
30	70,1	55,2	55,4	69,3	57,1	54,7	65,5	72,5
40	78,6	65,1	63,9	**78**	66,1	63,5	71,7	75,7
50	86,1	73	70,1	86,3	74,1	68	84	75,7
60	92,8	79,2	88,5	93,7	80,2	74,9	89,8	75,7

All temperatures measured in the experiment are plotted, Figure 9. Some snapshot with FLIR IC infrared imaging camera are presented in Figure 10 and Figure 11.



a) b)

Fig. 9. Temperatures measured in the case of 75bar pressure step: a) SITUATION I with suction throttle valve; b) SITUATION II without suction throttle valve.

Fig. 10. Pump FLIR IC snapshots in the case of SITUATION I, see Table 1 the bold numbers

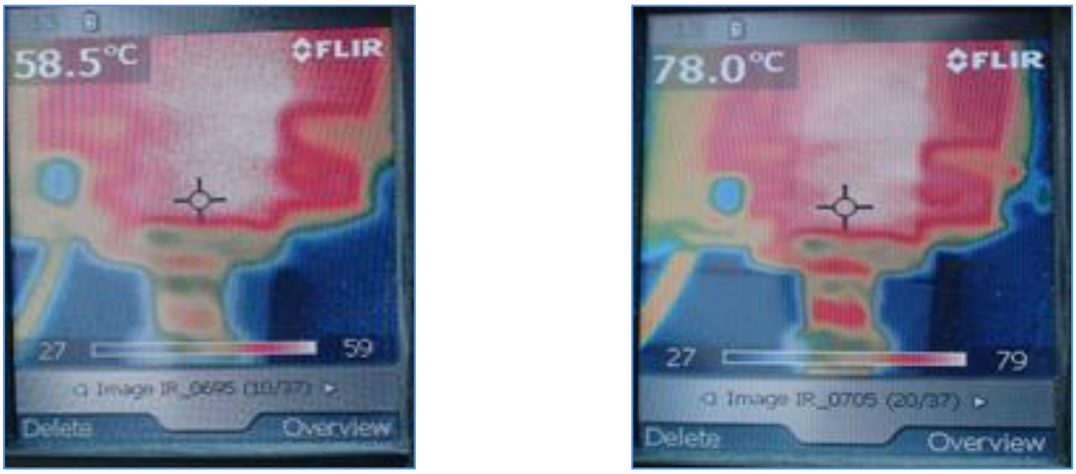


Fig. 11. Pump FLIR IC snapshots in the case of SITUATION II, see Table 2 the bold numbers

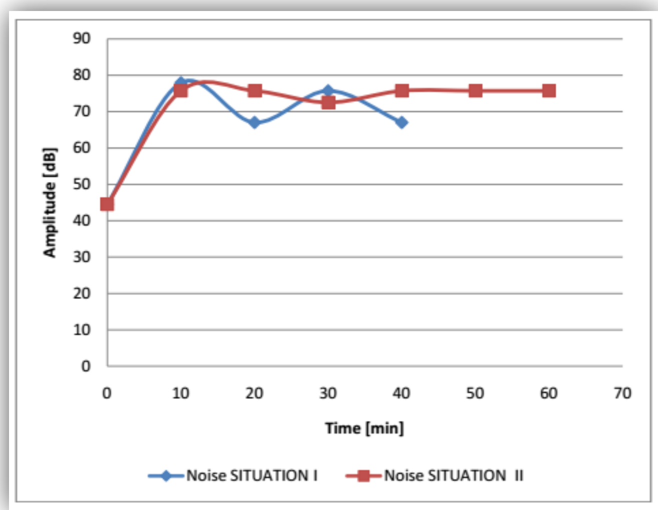


Fig. 12. Noise variation for 75bar pressure step

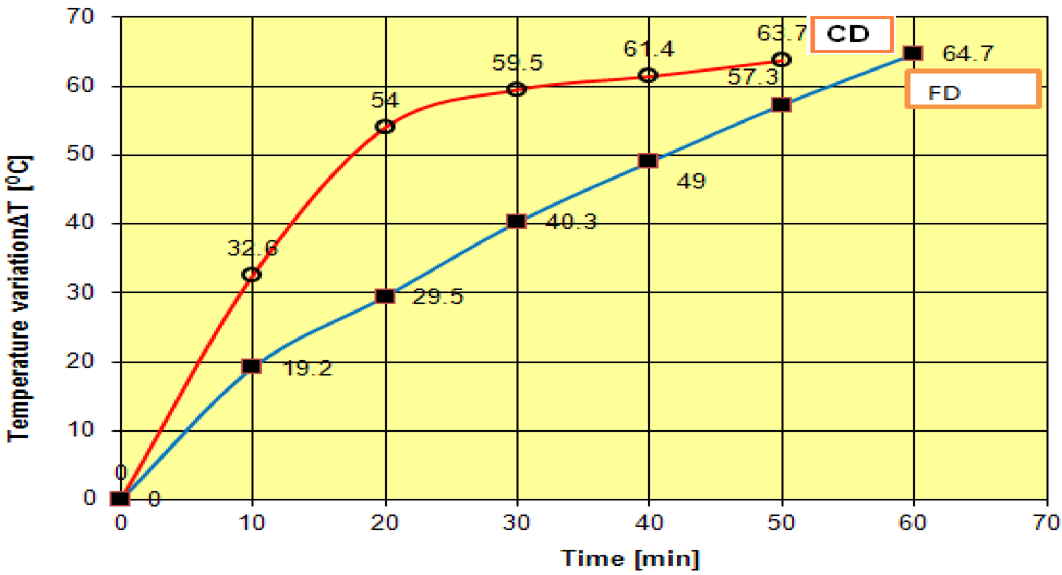


Fig. 13. Relative temperatures variation, for p= 75bar, with throttling (CD) and without throttling (FD)

Noise variation is plotted in Figure 12 for all period of the experiments in the two cases mentioned before.
Considering that the environment tempretaure is at the zero moment of time, according with the tables, at 25 °C (Table 1) and 29 °C (Table 2) the increased temperetaure on the pump measured with FLIR IC is plotted in Figure 13.

4. Discussions

Experimental results show that the pump measuring temperatures using contact thermometer are in accordance with the non-contact temperature measured with the FLIR thermal imaging camera, see Figure 9 and Figure 13. Also, it can be observed that the pump temperature, T_{pp}, measured with FLIR infrared camera keeps close enought for the considered standard temperature measured with contact thermometer, T_{CT_pp}, Fig. 9. It can be observed that the curve of temperature variation has the same trendline as the temperature curve plotted with full line in Figure 9. Even the temperatures measured with FLIR IC and infrared thermometer FLUKE IT have close values in the case of the reservoir temperature, T_{rez}, Fig. 9. Only the temperatures of the hydraulic oil cannot be compared, Fig. 9.a.
Considering the fact that the pump operating mode with different openings of the suction throttle valve is a simulation procedure of the pump in the case of a failure (i.e. cavitation), and comparing the pump temperatures in SITUATION II (without suction throttle valve) with the failure mode of operation (SITUATION I) it is observed the difference in the plotted temperatures, Fig. 9.
In Figure 9.b all the temperatures are "stick together" closer to the standard temperature line (T_{CT_pp}), in contrast with SITUATION I, Fig. 9.a. More than that, even the noise measurements warn us that the pump is in a failure mode of operation, Fig. 12.
In the discussion of experimental results we must be objective and recognize that the infrared thermography method has some limitations and method errors, calibration errors, signal errors can appear [6 ÷ 12]. For example the errors giving by the method occur because of an incorrect evaluation of the infrared thermography parameters. Commonlly, object emissivity, ε, atmospheric temperature, T_{atm} [K or ° C], ambient temperature T_0 [K or °C], humidity, ω [%], the distance between the infrared thermal imaging camera and the measured object, d [m] are some of them.
The influence of ambient radiation, directly or indirectly reflected by the object and detected by the camera is another thermography parameter not easy to evaluate and essentially in infrared image camera calibration.

5. Conclusions

The results of experimental research regarding the using of infrared thermography as method of condition-based maintenance were presented in the paper. The experimental simulations of a failure pump and the temperature monitoring with three different temperature devices help us to compare the behavior of the malfunction pump with the good one. The monitoring of noise was tested, too, as method in the maintenance of the hydraulic drives and the results confirm the connection between noise and the pump failure state.
In the paper is presented the test bench rig designed as a simple hydraulic circuit with a gear pump and a suction throttle valve mounted on the input of the pump to simulate the cavitation operating mode (named SITUATION I).
The normal operation mode was named SITUATION II.
Three steps of pressures were considered but only for 75bar the results were commented.
Analysing the temperature results we conclude that infrared thermography method can be used to monitor the behavior of a hydraulic drive system in the case of indoor hydraulic systems to avoid the influence of the environment in the calibration of infrared imaging camera.
The authors are intending to develop the procedure of infrared thermography maintenance method applied to hydraulic drives but the errors analyse of the measurements is necessary. Only with more temperatures data the experimental simulation can improve the infrared thermography method.

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References

[1] S.O. Duffuaa, A. Raoul, ”Planning and control of maintenance systems. Modelling and analysis”, Ed. Springer, 2nd Edition, 2015;

[2] R.K. Mobley, ”Maintenance Engineering Handbook”, 7th Edition, McGraw-Hill, Section 7. Instruments and Reliability Tools, 2008;

[3] A.D. Marinescu, T.C. Popescu, L. Enache, C.A. Safta, ”Researches on specific malfunctions diagnosis of hydraulic drive systems equipments using the infrared thermography method”, Proceedings of International Conference on Hydraulics and Pneumatics HERVEX – 22nd edition, Băile Govora (9-11) Nov. 2016, pp. 218-224;

[4] https://www.vivoil.com/it/prodotto/xp210/;

[5] A.D. Marinescu, C. Cristescu, T.C. Popescu, C.A. Safta, ”Assessing the opportunity to use the infrared thermography method for predictive maintenance of hydrostatic pumps”, 8 th International Conference of Energy and Environment -CIEM, Bucharest,Romania, 19 -20 October, 2017;

[6] A. Mihai, ”Thermography in infrared- Fundamentals” („Termografia în infraroșu- Fundamente”), Technical Publishing House, Bucharest, 2005;

[7] W. Minkina, S. Dudzik, ”Infrared Thermography, Errors and Uncertainties”, Wiley & Sons Publishing House, 2009;

[8] K. Chrzanowski, ”Non - contact thermometry – measurement errors”, SPIE, Vol. 7, Warsaw, 2000;

[9] R. Babka Robert, W. Minkina, ”Influence of calibration of an infrared camera on accuracy of sub-pixel edge detection of thermal objects, Measurement, Automation and Monitoring”, Vol. 48, No.4, pp.11-13, 2000;

[10] R.P. Madding, ”Emissivity measurement and temperature correction accuracy considerations”, Proceedings of the SPIE, Vol. 3700, 1999, pp. 393-401;

[11] A.D. Marinescu, C.A. Safta, T.C. Popescu, ”Advantages, errors and limitations of infrared thermography used to mantain hydraulic drive systems” („Avantajele, erorile și limitele termografierii în infraroșu utilizată la mentenanța sistemelor de acționare hidraulică”) – 17th Multidisciplinary International Conference ”Professor Dorin Pavel – the founder of Romanian hydropower” – Sebeş, Romania, (1-3) June 2017, published in ”Science and Engineering” („Știință și Inginerie”), ISSN 2067-7138, Year XVII, vol. 32/2017, pp. 65-74;

[12] Childs P.R.N., ”Practical Temperature Measurement”– Butterworth, Heinemann Linacre House, Jordan Hill, Oxford OX2, 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041, First published 2001.