Numerical Simulation of Thermal Processes Occurring at Testing Hydrostatic Pumps in Cavitation Mode

PhD.Stud. Eng. **Alexandru-Daniel MARINESCU[1],** PhD.Stud. Eng. **Alexandru-Polifron CHIRIȚĂ[1],** PhD. Eng. **Corneliu CRISTESCU[1],** Prof. PhD. Eng. **Carmen-Anca SAFTA[2]**

[1] Hydraulics and Pneumatics Research Institute INOE 2000-IHP, Bucharest, Romania
marinescu.ihp@fluidas.ro; chirita.ihp@fluidas.ro; cristescu.ihp@fluidas.ro

[2] Power Engineering Faculty, University Politehnica of Bucharest, Romania
safta.carmenanca@gmail.com

Abstract*: This article refers to the use of infrared thermography in the predictive maintenance of hydraulic drive systems. Based on experimental research on the temperature evolution in a hydraulic system which operates in cavitation mode, a numerical simulation model was built. The numerical simulation results are compared with experimental measurements in the points of interest of the hydraulic diagram versus numerical simulation model. The results obtained show that infrared thermal imaging camera procedure can be used in the limit of ± 10% errors as a predictive maintenance method in hydraulic drive systems.*

Keywords: *Maintenance, hydrostatic pumps, cavitation, infrared thermography, modeling, simulation*

1. Introduction

To maintain in working a long lifetime the hydraulic system at best parameters designed, predictive maintenance is widely used. Predictive maintenance techniques were developed to predict when maintenance should be performed. In 2001, CEN (Comité Européenne de Normalisation – French; European Committee for Standardization) defined the maintenance as "the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it may perform the required function" [1]. As maintenance defined above, two types of maintenance are developed: preventive maintenance (PM) and corrective maintenance (CM). Preventive maintenance is to control or prevent the deterioration process leading to failure of an engineering object, and corrective maintenance is to restore the engineering object to its operational state through corrective actions after a failure [1]. Through engineering objects one understands products, plants and facilities, infrastructures, assets and systems [1].

A good maintenance experience can compensate the unreliability of an engineering object.

The most common methods of predictive maintenance (as part of PM) are based on: oil analysis, vibration analysis, ultrasonic testing, and infrared thermography. The latter was used by the authors in the experimental research assessing the wear of a gear pump operating in cavitation regime [2].

The non-contact measuring temperature is a common method used in industrial maintenance [3]. The method was developed to avoid more energy consumption and the discontinuing production. Thermography is not a simple measurement method. It was demonstrate that the source of errors in infrared thermography are caused not only because of the incorrect evaluation of some characteristic parameters, such as the emissivity ε coefficient of the analyzed object, the atmospheric temperature T_{atm}, the ambient temperature T_0, the humidity ω, the distance between the termographic infrared camera and the measured object, d. The incorrect calibration or evaluation of absorption, reflection and transmission coefficients from the environment and the emergence of the electronic and photonic noise of the system are error sources too [4 ÷ 6]. In most cases, the professional solutions related to measurement errors minimization depends of the thermal imaging camera technical performance and the thermo technical knowledge of the one who uses it.

It is obvious that thermal regime of a hydraulic system is very important in the system design because a critical mode of working as cavitation mode can cause a premature failure of the basic components of the hydraulic system. Usually the hydrostatic pumps are exposed to failures.

Beside the experimental approach developed in INOE 2000-IHP laboratories regarding the infrared thermography maintenance method applied to hydrostatic pumps [2], a theoretical research was developed, too. In this paper a thermal numerical model of the hydraulic system tested in cavitation mode was simulated. The results of numerical simulations are compared in the critical points with the temperatures measured on the hydraulic schematic diagram.

2. Experiments

2.1 Experimental bench

The goal of the experimental study is to measure temperature evolution in time of one hour of a hydraulic drive system which is working in cavitation mode. An experimental bench was designed and physically developed in INOE 2000-IHP Labs, to allow the demonstration of usefulness and efficiency of using the infrared thermography method in the behavioural prediction of hydrostatic drive systems [2]. The hydraulic schematic diagram of the stand is shown in Fig. 1.

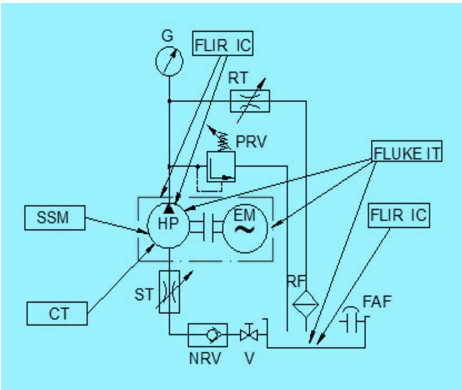

Fig. 1. Hydraulic schematic diagram

Fig. 2. Experimental bench for hydrostatic pump testing [2]

The bench consists of a tank (**T**), with hydraulic oil, provided 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 from the tank (**T**) via a valve (**V**) and a non-return valve (**NRV**) to keep the oil suction circuit filled of oil, as well as a throttle (**ST**), by which the suction circuit of the pump can be modified (strangled or throttled) in order to modify the suction conditions. The flow section variation through the throttle will lead to an increase of the operating temperature, a phenomenon that will be sensed, measured and recorded by an infrared thermal imaging camera **FLIR**. The hydrostatic pump (**HP**) displaces the oil under the pressure indicated by the pressure gauge (**G**) and is adjusted to the pressure limiting valve (**PRV**) by means of a throttle (**RT**) mounted on the pump discharge, which allows the desired pressure steps to be achieved. The oil will be returned to the tank (**T**) by a return filter (**RF**). In figure 2 is presented the experimental bench.

Fig. 3. Fluke infrared thermometer

Fig. 4. FLIR infrared thermal imaging camera

The experimental bench is used to test a hydrostatic gear pump which is one of the most used types of pump in hydraulic drive systems. The bench was designed so that the pump testing can

operate at different pressure stages controlled by RT throttle and different suction conditions controlled by ST throttle. The experimental studies have been made in cavitation suction mode.
The unwelcome cavitation phenomenon is a complex one: mechanical, thermal, hydrodynamic and chemical. Depending on the flow conditions, the phenomenon of cavitation occurs in the flow of liquids through hydraulic machines and equipment regardless of their application [7, 8]. The cavitation phenomenon occurs when the liquid pressure drops below the liquid vaporization pressure, $p < p_v$. So, if the flow rate is constant but the flow section is narrowing (as on a throttle valve ST) the flow velocities in the flow section are increasing and the pressures are decreasing (Bernoulli equation). Due to the initiation of the vaporization phenomenon, clouds of cavitation bubbles or cavities filled with gas and liquid vapours are formed. Cavitation bubbles are transported by liquid flow in high pressure areas where their implosion occurs. At the time of implosion, the pressures which are developed are several orders of magnitude larger than the average liquid pressure. Once the cavitation phenomenon has developed, the heating process of the liquid is accelerated, the flow hydrodynamic is changed and a biphasic flow (liquid and gas) appears and the efficiency of the system will decrease.
The cavitation phenomenon can be controlled and monitored [9].
In cavitation mode of working on the suction pump in the test bench, environmental temperature, oil temperature, and pump temperature were measured along one hour with a time period of 10 minutes. Pump temperature was measured with three types of temperature devices: a contact thermometer (**CT** type Checktemp 4 by Hanna) directly placed on the pump, a **FLUKE IT,** Fig. 3, infrared thermometer and a **FLIR IC** infrared thermal imaging camera, Fig. 4. Tank and oil temperatures were measured with the same devices FLIR IC and FLUKE IT contactless infrared thermometer. During the experiments the working pressure was read on the manometer (**G**), and the noise in the installation was monitored with the Smart Sensor (**SSM** - Smart Sensor AR 814) soundmeter.

2.2. Experimental results

Temperatures of the pump, tank and oil are measured in working conditions of 75bar pressure step and cavitation. The data are listed in Table 1 where the type of temperature device used is mention too. The temperature at moment zero in the table coincides with the environment temperature.

Table 1: Measured temperatures

Time	T pump FLUKE	T pump FLIR	T tank FLUKE	T tank FLIR	T oil FLUKE	T oil FLIR
0.0	24.0	24.0	24.0	24.4	24.0	24.0
10.0	40.0	41.0	28.0	27.5	28.5	29.5
20.0	51.0	57.2	31.0	31.4	32.0	33.9
30.0	72.0	78.4	42.0	45.5	33.0	49.8
40.0	77.0	84.1	46.0	47.0	65.0	58.9
50.0	83.0	76.0	50.0	51.8	60.0	60.2
60.0	80.0	88.3	50.0	54.0	63.0	60.5

Fig. 5. Thermographic images taken with FLIR Infrared Thermal Imaging Camera

Figure 5 presents the thermographic images, obtained by temperatures measured with the FLIR thermal imaging camera and highlighted in Table 1.

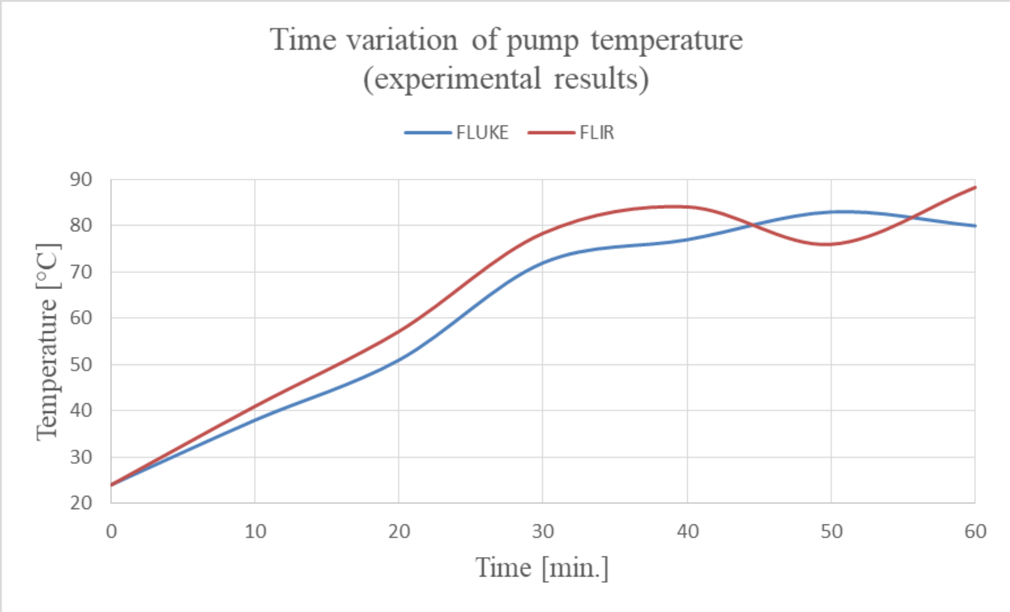

Fig. 6. Trend graph of measured temperatures with Fluke IT and FLIR IC

Based on data from Table 1 the pump temperatures behaviour was plotted in Figure 6, in the case of using the FLUKE IT and FLIR IC devices.

3. Numerical simulation of thermal processes

A theoretical study of the thermal behaviour of the gear pump working in cavitation regime was performed. A numerical simulation network was considered and the points of interest of the hydraulic schematic diagram (Fig. 1) were analyzed in the numerical simulation model, too.

3.1 Developing the Numerical Simulation Network, NSN

Starting from the hydraulic schematic diagram of Figure 1 with the physical parameters of Table 2 there was built the numerical simulation network with the diagram plotted in Figure 7.
Simulation software AMESim from SIEMENS LMS Imagine.Lab was used [10]. The NSN was designed to simulate the thermal processes in the experimental bench of the hydrostatic gear pump working in cavitation mode in the same conditions as experiments.

Table 2: Physical parameters of simulation

NSN Index	Name	Parameters	NSN Index	Name	Parameters
1	Hydraulic oil tank	Capacity - 20 l	**5**	Electric motor	Speed - 1450 rev/min
2.1	Hydraulic hose	Nominal size Ng - 25 mm	**6**	Hydraulic gear pump	Pump disp. - 9 cc/rev
2.2	Hydraulic hose	Nominal size Ng - 10 mm	**7.1**	Volumetric flow rate sensor	
2.3	Hydraulic hose	Nominal size Ng - 10 mm	**7.2**	Pressure sensor	
2.4	Hydraulic hose	Nominal size Ng - 10 mm	**7.3**	Temperature sensor	
2.5	Hydraulic hose	Nominal size Ng - 10 mm	**8**	Hydraulic pressure valve	Cracking pressure - 75 bar
2.6	Hydraulic hose	Nominal size Ng - 10 mm	**9**	HP46 hydraulic oil	Kinematic viscosity - 46 cSt

Table 2: Physical parameters of simulation (continued)

NSN Index	Name	Parameters	NSN Index	Name	Parameters
3.1	Pump inlet throttle		**10**	Earth attraction constant	9.80665 m/s^2
3.2	Pump relief throttle				
4.1	Constant signal source				
4.2	Constant signal source				

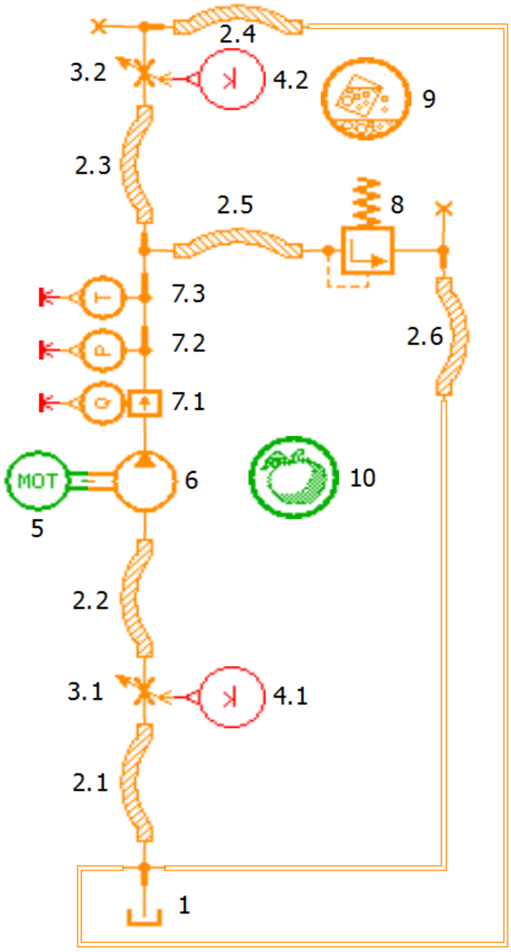

Fig. 7. Numerical simulation network, NSN

The same hydraulic elements used in the hydraulic schematic diagram were modelled with corresponding blocks of the thermal hydraulic library in LMS AMESim ® together with physical parameters of the hydraulic system. The numerical model does not take into account the heat exchange of the hydraulic system with the environment.

3.2 Numerical simulation results

The simulation results are drawn in the following graphs.
Figure 8 shows the pressure variation on the pump intake (green colour) and the output pressure variation of the pump (red colour). The existence of the accentuated vacuum (about 0.4 bar) on the pump input is highlighted which corresponds to cavitation operation mode of the pump at the narrowed flow section controlled with the throttle (**ST**). On the graph one can notice the output pump pressure, which highlights the value set for the safety valve (73 bar), and a slight mitigation in time, caused by heating the oil or lowering the viscosity of the oil.

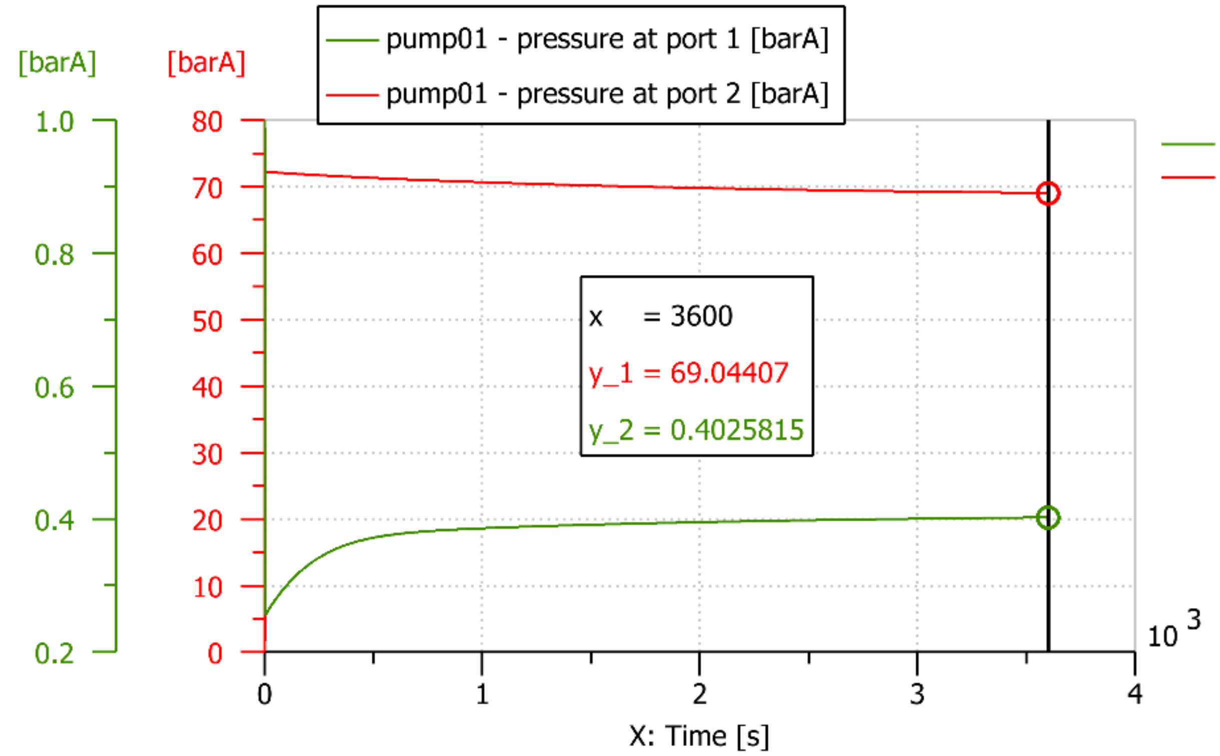

Fig. 8. The pressure developed at the inlet and discharge of the hydraulic pump

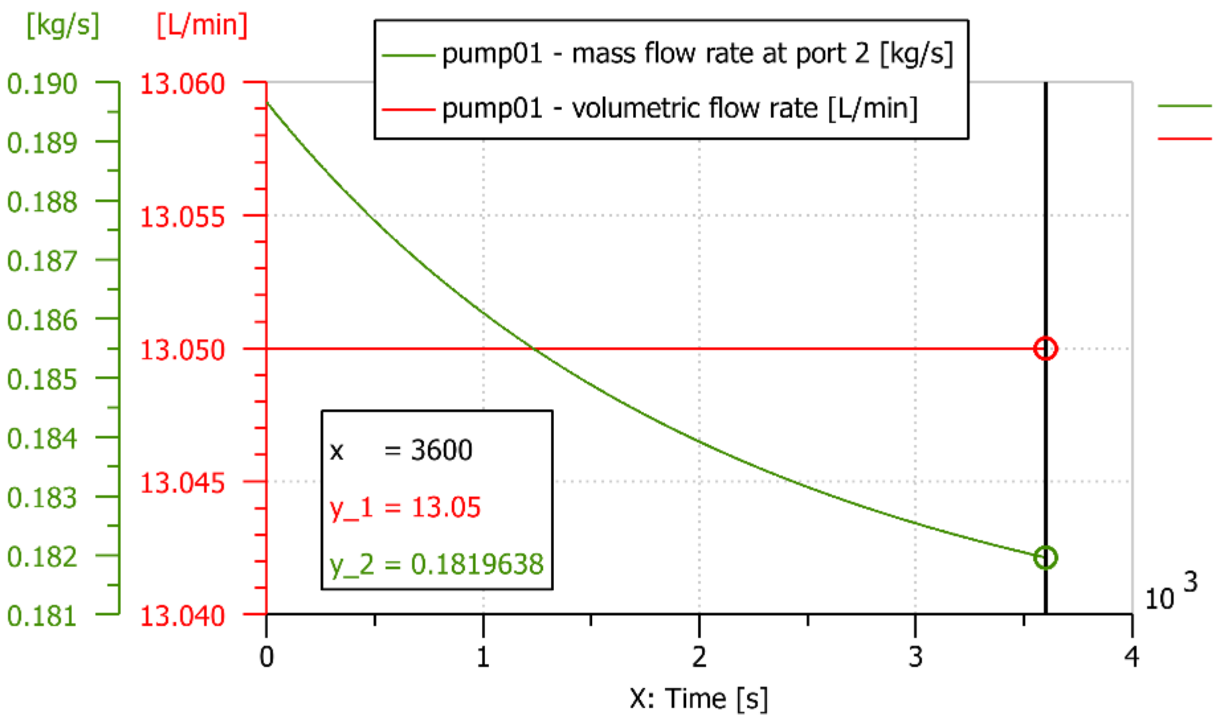

Fig. 9. Volumetric and mass flow of the hydraulic pump

Figure 9 depicts both the pump flow variation (red), and the change in mass flow to the pump (green), which has an interesting dash explainable also by increasing the temperature that makes the density of the oil decrease.

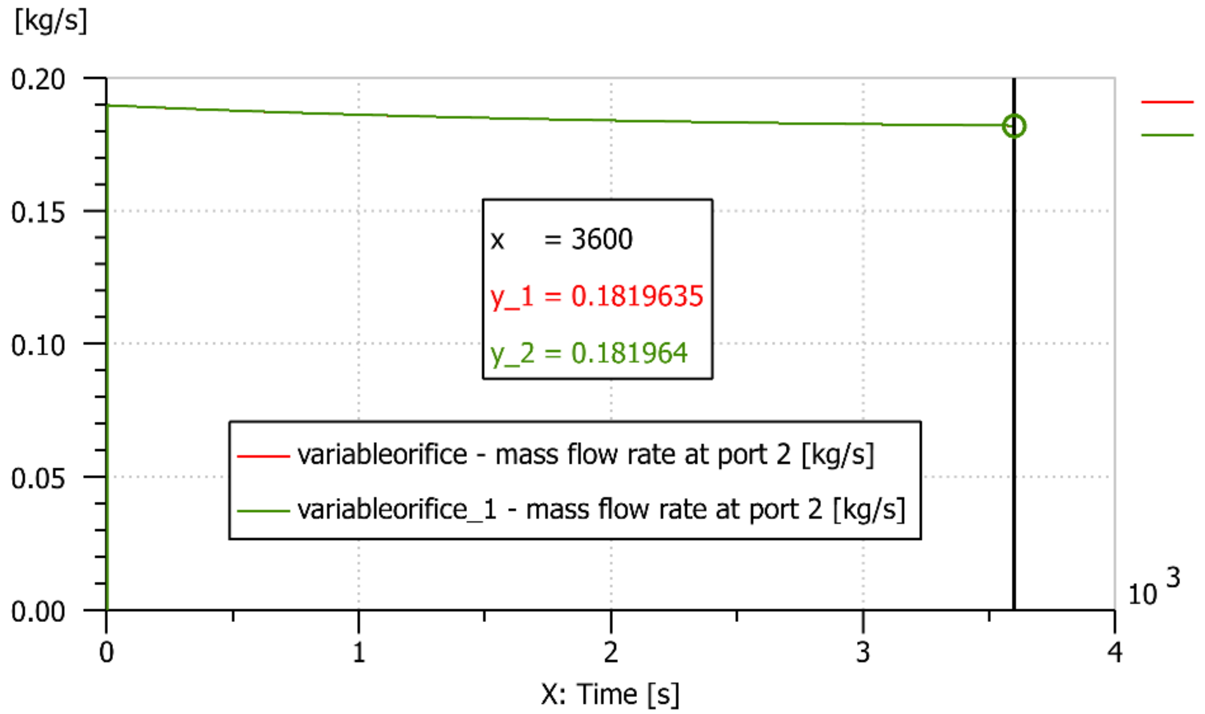

Fig. 10. Mass flow through the hydraulic orifices (throttle)

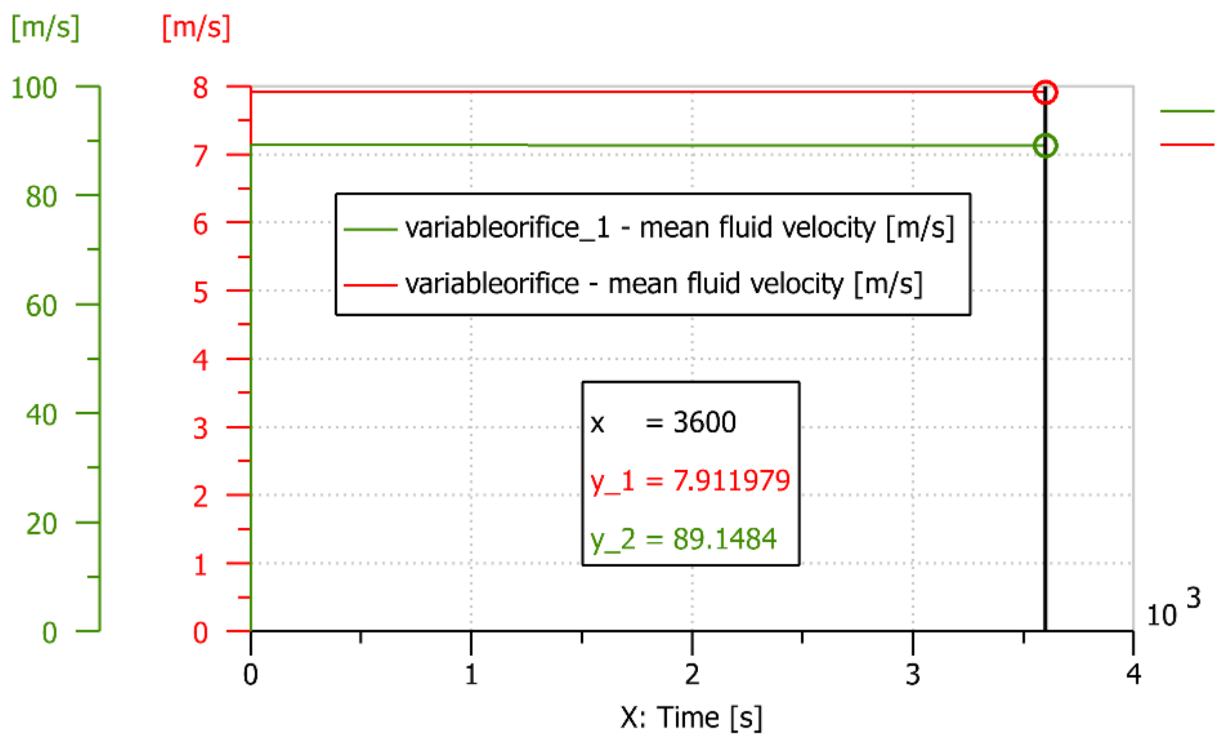

Fig. 11. Velocity of liquid through the hydraulic orifices (throttle)

Figures 10 and 11 show the variation of the mass flows through the throttle holes (almost identical), respectively the variation of the oil flow speeds through the throttle holes on the pump discharge circuit (red 3.1) and respectively on the circuit (green colour 3.2), the latter having lower values because the suction diameter is higher (NRN Index 2.1).

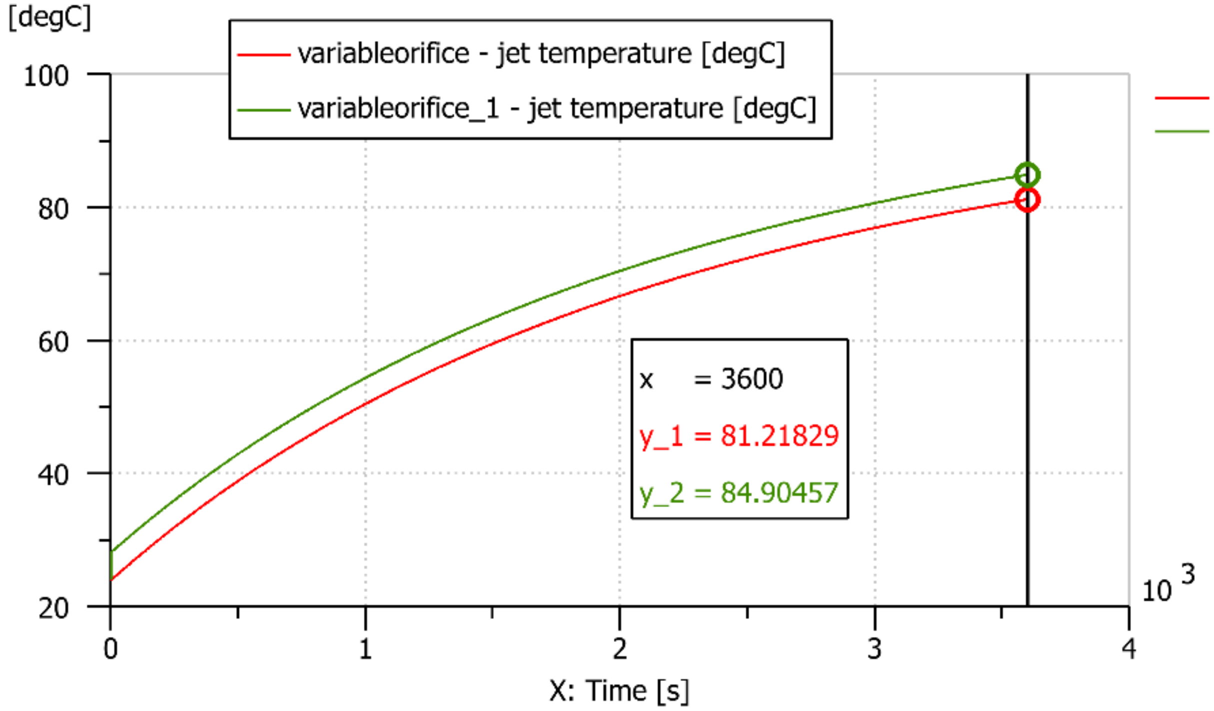

Fig. 12. Liquid stream temperature through the hydraulic orifices (throttle ST and RT)

Figure 12 shows the variation of the oil temperature in throttle holes, with red on the suction circuit, and with green on the discharge circuit, the aspiration being somewhat higher due to the hard cavitation regime.

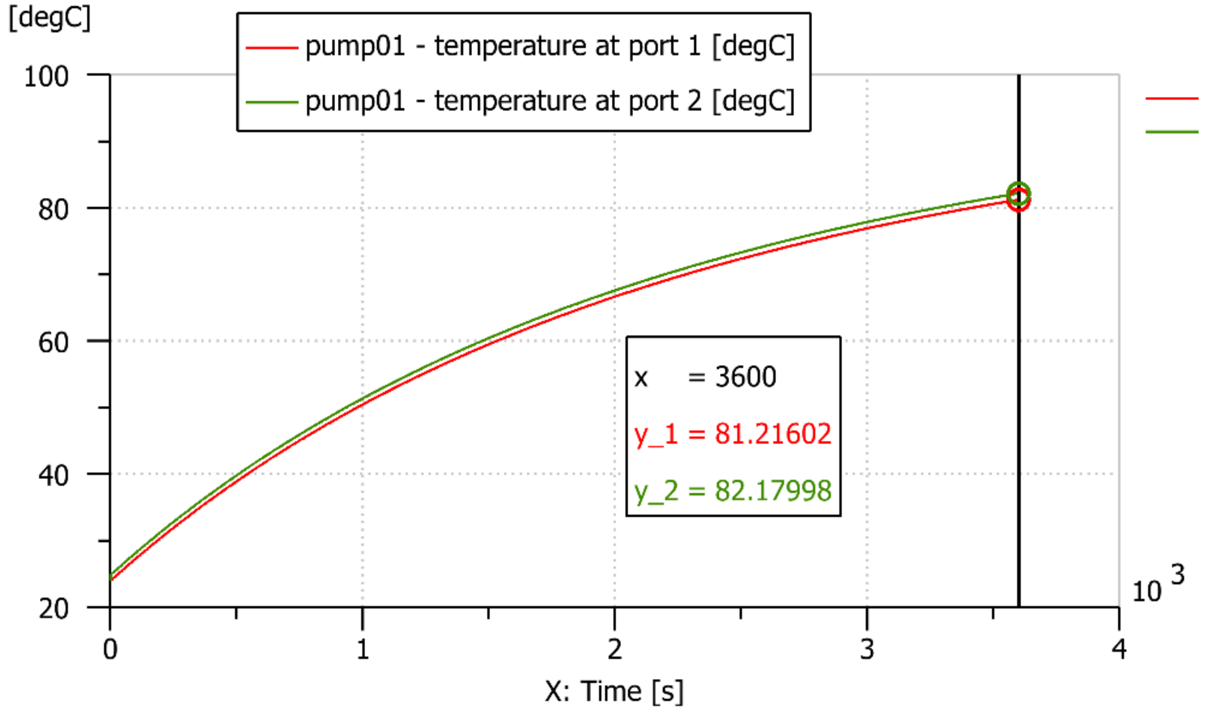

Fig. 13. Fluid temperature in pump inlet and discharge

Figure 13 shows the temperature variation at the pump inlet (green colour) and pump discharge (red colour) which is slightly smaller than the pump temperature because of heat exchange.

3.3 Comparative analysis of experimental and theoretical results

The temperature measurement results from experiments, Table 1, were compared with numerical simulation results. Figure 14 presents on the same graph the measured values with the FLUKE IT (red), FLIR IC (green) thermal imaging cameras and numerical simulation temperature of the pump (blue colour). A good match between experiment and numerical simulation is noticed. The experimental values measured with the FLUKE IT infrared thermometer (red colour) are closer to those obtained by numerical simulation (blue colour). Temperatures measured with FLIR IC infrared camera are not so close to the numerical temperature values. As mentioned in [2], the experimental procedure of using infrared thermography must be improved to minimize the uncertainty of the method.

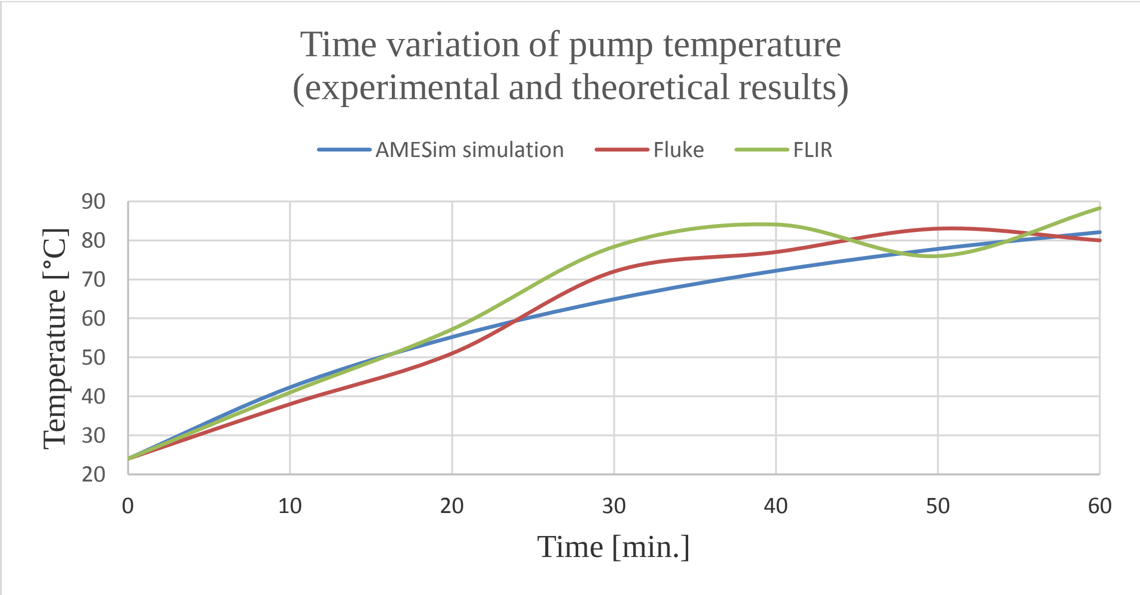

Fig. 14. Hydrostatic pump temperature

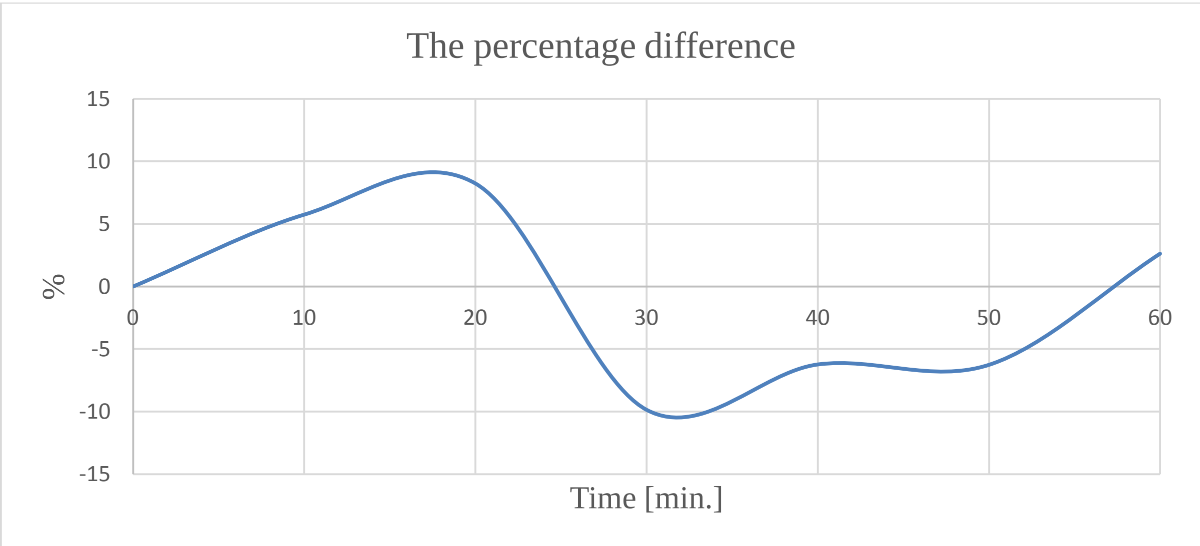

Fig. 15. Percentage difference

To highlight the difference in value between those obtained by measuring with FLUKE IT and those obtained by numerical simulation, in Figure 15 was plotted the percentage of variation differences that are between -10% and 10%, which represents an acceptable error taking into account the complexity of the hydraulic system and the hypothesis of the theoretical study that there is no exchange heat between installation and the environment.

The resumption of the experimental measurements, in a more accurate manner, and a more accurate simulation model will lead to a smaller error between the experiment and theoretical model.

4. Conclusions

The article presents a theoretical study based on experimental measurements of temperatures on a hydrostatic pump bench test performed in INOE 2000-IHP Labs. The goal of the study was to validate a numerical simulation model of the thermal process in a hydraulic gear pump test bench with experimental temperature measurements in the points of interest of the hydraulic system.
In the first part of the article, besides general knowledge regarding preventive and predictive maintenance, it is presents the test bench and some experimental temperature measurements of pump, oil and tank temperatures by using a thermal imaging camera and an infrared thermometer.
The second part of the article presents the theoretical research itself, which consists in the development of a numerical simulation network based on the physical hydraulic diagram and data of the physical model under investigation. Numerical simulation results were plotted and compared with experimental results. A good evolution of temperatures was noticed between the FLUKE IT and numerical simulation results under an error of ± 10%.
This experimental and theoretical approach of a hydraulic system having a gear pump which is working in cavitation mode highlight that the experimental results obtained by using the FLUKE infrared thermometer are closer to the theoretical results obtained by numerical simulation, and so, this device can be a base for development of a predictive maintenance method.

Acknowledgement

Thanks to Hydraulic and Pneumatic Control Systems Labs within Power Engineering Faculty from University Politehnica of Bucharest, for the support in using AMESim, for thermal process simulation.

References

[1] Ben-Daya, Mohammed, Uday Kumar, and D. N. P Murthy. *Introduction to maintenance engineering: modeling, optimization, and management*, John Wiley & Sons, 2016.
[2] Marinescu, Alexandru Daniel, Corneliu Cristescu, Teodor Costinel Popescu and Carmen Anca Safta. "Assessing the Opportunity to Use the Infrared Thermography Method for Predictive Maintenance of Hydrostatic Pumps." Paper presented at the 8th International Conference of Energy and Environment - CIEM, Bucharest, Romania, October 19 -20, 2017.
[3] Mihai, Al. *Infrared Thermography. Basics*/*Termografia în infraroşu*. *Fundamente*. Bucharest, Technical Publishing House, 2005.
[4] Badea, Adrian, Aureliu Leca, et al. *Processes of heat and mass transfer in industrial installations* /*Procese de transfer de căldură și masă în instalațiile industriale*, Bucharest, Technical Publishing House, 1982.
[5] Childs, P. R N.. *Practical Temperature Measurement,* Butterworth Heinemann, 2001: 238-287.
[6] Minkina, W., and S. Dudzik. *Infrared Thermography. Errors and Uncertainties*. John Wiley & Sons, 2009.
[7] Anton, Ioan. *Cavitation*/*Cavitatia*, vol. II. Timisoara, Publishing House of the Academy, 1985.
[8] Sandor, Ianos Bernad. *Hidrodinamica echipamentelor de reglare pentru actionari hidraulice*. Timisoara, Orizonturi Universitare Publishing House, 2005.
[9] Băran, Gheorghe, Ilie Catană, Ioan Magheți, Carmen-Anca Safta, and Mariana Savu. "Controlling the Cavitation Phenomenon of Evolution on a Butterfly Valve." Paper presented at the 25th IAHR Symposium on Hydraulic Machinery and Systems, Timisoara, Romania, Sept. 20-24, 2010.
[10] ***IMAGINE S.A. *Advanced Modelling and Simulation Environment*, Release 4.3.0 User Manual, Roanne, 2006.