# CONTAMINATION CONTROL OF HYDRAULIC SYSTEMS IN INDUSTRY 4.0

***Marko Orošnjak, Faculty of Technical Sciences, University of Novi Sad, Serbia***
***Mitar Jocanović, Faculty of Technical Sciences, University of Novi Sad, Serbia***
***Velibor Karanović, Faculty of Technical Sciences, University of Novi Sad, Serbia***
***James Wakiru, KU Leuven, Centre of Industrial Management, Belgium***
***Uglješa Bugarić, Faculty of Mechanical Engineering, University of Belgrade, Serbia***

***Abstract:*** *This paper describes the expansion of maintenance in Industry 4.0 concerning contamination control ofa hydraulic systems. Recently, a lot of attention is dedicated towards newly coined term of Industry 4.0, therefore maintenance 4.0, Industrial Internet of Things, Internet of Condition Monitoring, etc. Contamination control as an integral part of Condition Based Maintenance takes a significant part in diagnostics and prognostics of systems containing hydraulic fluids. Hydraulic fluid as a driving medium in hydraulic system suffers from material and energy contamination. The influence is seen through degradationof physical and chemical properties of the hydraulicoil. Recently, in condition monitoring techniques, as a maintenance strategy, a lot of authors emphasize using particle influence as a pre-warning sign in detecting potential failure. Therefore stakeholders in the industry ((engineers and technicians)follow that claim and consequently implement the strategy therby purchaseand install new sensors and equipment in order to eliminate and mitigate system stoppage or reduction in performance. In this paper, however authors propose a slightly different aproach in trend analysis over particle contamination, and that is, using viscosity change as a pre-warning sign. Besides, authors advocate techniques and methods needed in adequate contamination control of a system.*
***Keywords:*** *contamination control, tribology, maintenance, condition based maintenance, oil diagnostics*

## INTRODUCTION

Modern hydraulic systems experience a constant increase in power demand, energy efficiency andhigher reliability of components,while considering environmental protection. Particularly, hydraulic fluids requires an inclusive consideration, herewith the hydraulic fluidhas to be considered as the most important component of a hydraulic system. There are few examples how an oil cleanliness influence the performance of the system overall, such as: actuator'sresponse, internal structure of components, influence on flow and pressure, reliability of components, environmental influence, loss of power and most of all degrading the physical and chemical properties of the oil itself/1/. Therefore, the influence of cleanliness of the oil is more than evident.To reduce or in some cases avoid unnecessary loss of power, some sort of maintenance strategy has to be applied in order to fulfill the requirements of application. Far and the foremost important maintenance strategy is Condition Based Maintenance (CBM).

Contamination of hydraulic control system has long been recognized as one of the major causes of components wear due to oil degradation/2/. Considering the fact that oil reflects the state of the system the same way blood analysis reflects the condition of a human, monitoring an oil plays a vital role in maintenance decision making while ensuring the quality performance of the system. Lubricant Condition Monitoring (LCM) is one of the most important condition monitoring techniques ultilized on a planned or scheduled maintenance period /3/.LCM is an essential tool as prognostic and diagnostic aspect of CBM, which aims towards better understanding of machine's root failure cause, Remaining Useful Life (RUL) of machines, shortening mean time between failures, contributing to higher reliability and similar. In order to consider applying LCM on a realistic system maintenance technicians and engineers must fully understand the equipment working regime, cycles, component requirement cleanliness level, working environment, system working temperature, type of oil applied in the system, additives in the oil and instruments and methods applied in prognostic and diagnostic of the system.The reason for the aforementioned is thatoil contamination can damage the system in numerous ways. Examples of damage from contaminants are: loss of lubrication and accelerated wear, blockage of flowing paths, formation of rust or other oxidation,

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

depletion of additives, formation of acids and other chemicals which have negative influence, oil degradation /4/.

In order to prevent the failure or to prolong RUL adequate CBM technology must be applied, especially in the era of strict user's requirements which is forcing Original Equipment Manufacturers (OEMs)to conduct more accurate and sophisticated measurement. For example, Rolls Royce is using Engine Health Monitoring technique (EHM) with 25 sensors constantly monitoring Rolls Royce Trent engine. With such real-time data OEMs can diagnose the condition of products whilst still in operational mode and prevent failures /5/.

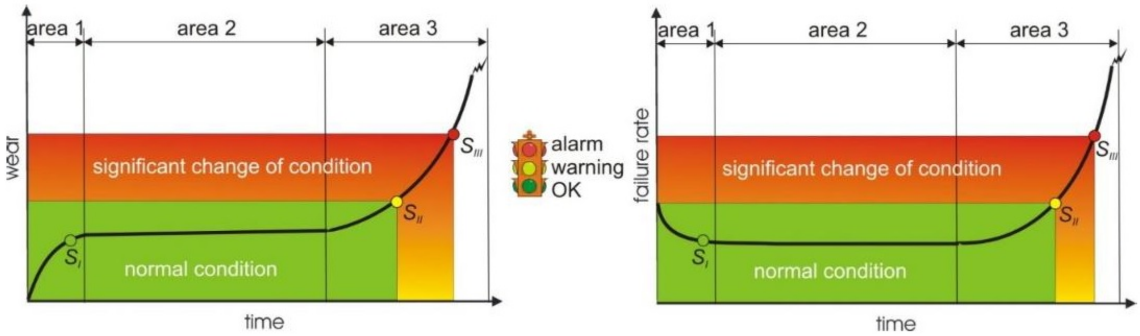
## *MOTIVATION FOR THE RESEARCH*

Hannover Messe 2011, one of the largest technology fairs, has been a creator of state-of-the-art term "Industrie 4.0". Although the ideology of Industry 4.0 implies data exchanges, robots, big data, cloud, IoT, smart technologies and has been priority for many companies, centers and universities, generally accepted understanding of the term is still not explicitly defined/6/. Even so, paradoxically, technological development of Industry 4.0 has been widely accepted and followed by maintenance 4.0 as an integral part. However, the notion of Industry 4.0 and concept of Internet of things can be understood as availability of all relevant information in real time data by all parties involved in value creation.

Recently,OEMs of high value products provide maintenance and service packages to customers in order for their products to be at peak efficiency throughout their RUL. In recent decades, the aerospace industry has become an expert in using real time data for the purpose of monitoring and maintenance scheduling /7/, where the real time data is transfered back to manufacturer where diagnostic and prognostic analysis takes place. Same principle is taking over the construction and automotive industries. All things been said, the lack of knowledge, technology and methodologies in monitoring and processing data from the system led authors to beleive that industrial sector is skipping a few steps and automatically implementing state-of-the-art technology forced by their CEO's. Therefore, motivation for the research was provoked by generally wrong understanding of key indicators as warning signs of contamination in hydraulic systems hence leading to inadequate monitoring techniques and inappropriate maintenance strategy.

## *CONTAMINATION CONTROLIN HYDRAULIC SYSTEMS*

Contamination control is necessary in preserving the integrity of hydraulic systems. Contamination control is considered as a broad subject that is applicable to all material systems which is concerned with planning, organizing, managing, and implementing all activities in order to determine, achieve and maintain specified contamination level of a system /8/.One of the most famous pedlar of contamination control of hydraulic systems prof. E.C. Fitch distinguished two groups of contaminants: material and energy.From which gas, liquid and solid particles belong to material contaminants; whilst thermal, mechanical, chemical, electrical, magnetic and radiant belong to energy contaminants.




*Picture 1. Wear of components and level of damages throughout machine's service life /9/*

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

Another type of classification can be distinguished as particle contaminants (wear debris of metal particles and dirt ingression) and chemical contaminants (water, air, microbes, etc, which causes chemical reaction with fluid or/and material of components). Authors will emphasize discussion over particle contamination, which is considered the most damage producing phenomenon in the system, although the influence of water, heat, air, should not be omitted by any means necessary.

There are different types of failures in hydraulic systems, depending on the wear process. For example, infant mortality or failures on the start (area 1 on picture 1), failure in service mode (area 2 on picture 1) and final mortality (area 3 on picture 1) with components wear out or fatigue.

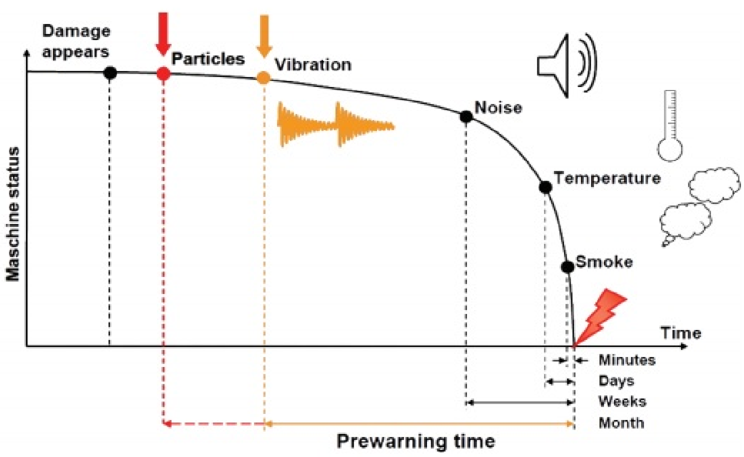
Great number of failures are caused by inadequate oil cleanliness or by wear out of components due to particle contamination. Particles and debris can enter the system in many ways, thus particle contamination sorting is given as following:

- Built-in contamination. Contaminated hydraulic system during manufacturing and assembling (welding slag, dirt and particulate) and contaminated new oil (during manufacturing, handling and storage).
- Ingressed contamination. This type of contaminants enter the system through breather cap, dirt sticking to cylinder rod, or disconecting the system for maintenance.
- Internally generated contaminants. This type of particle contamination is the most dangerous one, because it is generated due to material removal from inner surfaces of components (wear process by abrasion, adhesion, fatigue), and then circulated through the system damaging other components.

Internally generated particles influence the system in numerous ways, such as: damaging pump housing and other internal structures of components within the system, heat generation, slower actuator response, energy dissipation, etc.

## *CONDITION MONITORING OF HYDRAULIC EQUIPMENT*

Condition monitoring measurements are based on application of advanced methods of signal acquisition, processing and conditioning /10/. Data used for diagnostics and prognostics,must be extremely well processed and accurate, in order to get a proper feedback of the system health. This is important for machines that operate 24/7, under extreme conditions and stringent deadline schedules where constant monitoring of the equipment is required. Based on montoring techniques failure can be prevented and prolonged, which depend on pre-warning signaling. There are numerous pre-warning signs advocated by authors /10-11/ to prevent system from degrading more or damaging the components, which is illustrated in picture 2.




*Picture 2. Pre-warning time /9,10/*

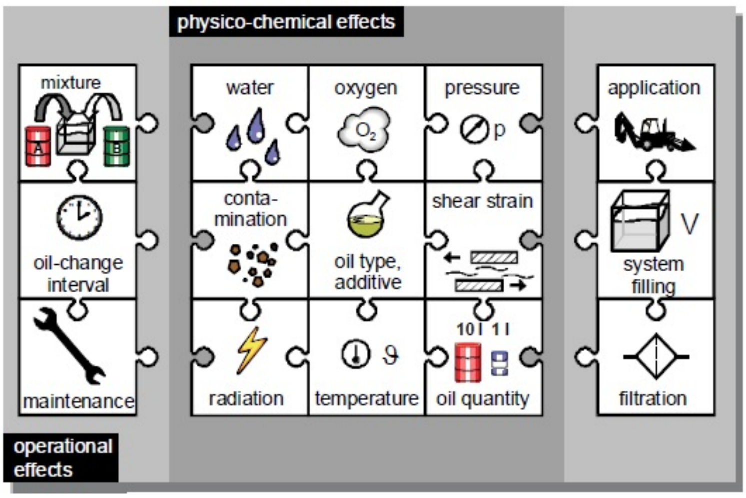
*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

As it can be seen from the Picture 2 that pre-warning signals can be numerous based on the state of degradation of the system. This doesn't necessary has to be the case for all type of machinery, but for hydraulic system overall can be adopted.

Condition monitoring of the hydraulic system is divided into two groups: online and offline method. Usually, these two are separated by analysis off- and on-site. By performing an offline method a sample is taken to the laboratory where data is acquired concerning system health, or more accurately, the oil characteristics. These results take some time but are usually more accurate than results provided by the online monitoring techniques. One of the examples is that results by inline Automatic Particle Counters (APCs) can show discrepancies up to $\pm$ 1÷2ISO 4406:99 class level comparing to high precision laboratory instrument /12/. ISO cleanliness level in hydraulic system has essential influence on the flawless function of components. Maintaining the required cleanliness level and monitoring the filters, give information about the oil and components state. One of the simplest forms of monitoring contamination is filter bypass signal. Filter bypass-signal with differential pressure indicator (according to DIN 24550) represents the rise of captured contaminants in the system. For example Vickers indicators are designed to indicate at a pressure drop of 20% below the bypass setting which equates at 95% of the element's service life /13/, therefore indicating the end of service life of a filter.This filter wear debris can be sent to offline analysis by high precision instruments such as ICP/OES (Inductively coupled plasma atomic emission spectroscopy) to analyze the presence of metal particles in the oil. Based on that analysis it can be concluded which components of the system are damaged. For example, Ng /7/ emphasized that iron and copper are the key indicators on hydraulic components wear rate, which was concluded by ICP/OES analysis of oil in the excavator.

Monitoring the particle contamination in the system are usually done by Automatic Particle Counters (APCs). Namely, particles rise within the system (in accordance with ISO4406) could represent pre warning sign before vibration, noise, smoke and failure of the part. Although if one, for example, considers the drop/raise in viscosity, it is clearly that graphicon picture 2 could be modified. The reason will be discussed later on in the paper. On the other side, if the equipment is working in an adverseenvironment like construction machinery whereasparticlesrise over cylinder rod (sticking), graphic could be somewhat acceptable.

Beside monitoringparticles rise within the system, a lot of different methods can be used to qualitatively and quantitatively determine the state of the oil and the system. Changes can be tracked by monitoring and analyzing viscosity, temperature, pressence of water and air,and other physical and chemical parameters (picture 3).

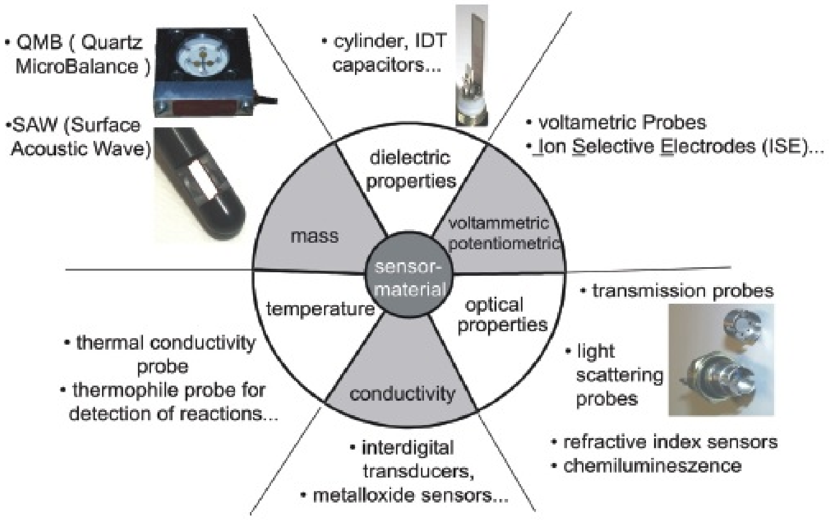



*Picture 3. Influence of oil deterioration process /10,15/*

Considering the importance of measuring the desired parameters of the system, maintenance managers and engineers can determine the sensors needed. Some authors /7,9,14/ advocate that the priority sensors

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

should be particle counters, although authors of this paper propose than in some cases other sensors can give even earlier signs of system performance degradation. Even so, authors do not neglect that its the most popular method for oil and system diagnostics.




*Picture 4.Sensors principles /15/*

Taking into account that real-time data measurements are needed with equpment working around-the-clock laboratories cannot be considered in data management, and the reason is time limitation. Stoppage in industrial machinery is directly related to loss of production and expences. However, using online sensoring can provide trend analysis, while laboratory procedures provides detailed information needed to analyze the trend. Service and maintenance measures are implemented based on the measurement results/10/.The most important physical and chemical changes in hydraulic oil can be detectedusing robust and cost-effective on-line sensors, working on different principles (picture 4).

*Picture 5. Viscosity sensors*

Whilst automatic particle counter can play a significant role in early detection of wear in hydraulic system, authors propose that trend analysis from viscosity also can play a crucial role of pre warning sign. This can be done by measuring viscosity by an inline viscosity instruments (picture 5).

## DISCUSSION

As mentioned, not all conditions,which are influenced by external or internal problems, may lead to failure due to particle contamination as a root cause. Sufficient portion of that can be attributedto viscosity drop by contamination. The drop in viscosity, which is influenced by many factors, can lead to metal-metal contact within and among the hydraulic system components. Critical components like the hydraulic pump suffer the most duering this wear process.. Therefore, a distinction should be made between pre-warning signs of potential failure.

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

Since the viscosity is a measure of fluids's internal friction or its fluidity: its resistance to flow reflects the response of a system, because the fluid is the one transfering the energy from mechanical – hydraulic – mechanical. Changes in viscosity affects performance of a system because the physical properties of the oil changes due to change in viscosity. Among other physical stability properties (picture 6) of a fluid, viscosity and viscosity index are considering the most important ones in hydraulic fluids /16-17/.

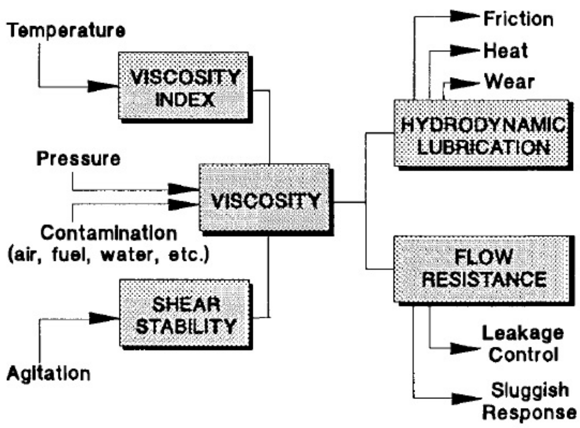
Viscosity, depending on temperature, pressure and contamination, can rise or fall. Excessively high viscosity can produce several system problems, such as: high pressure drops, pump cavitation, high power consumption, etc. On the other side a drop in viscosity can even be more devastating to a fluid system than the viscosity increase, leading to: high internal leakage, excessive wear on moving parts, poor lubrication, external leakage, etc.


*Picture 6. Physical stability properties of fluids and system operations /16/*

As oil viscosity decreases, the lubricating film thickness decreases leading to metal-to-metal contact and wear occurs within that contact pair. Hence, particles rise which can be followed by more damage from other components, while that wear debriss is circulating throughout the system.

Since the temperature is cosidered the most damaging parameter affecting viscosity, engineers and managers usually implement components like heat exchangers in critical systems. Beside temperature, pressure also significantly affects viscosity change. Viscosity changes occur during each pass of the fluid through the hydraulic circuit.

A simple illustration of viscosity influences are given in picture 7. Another thing that shouldn't be left out of the discussion is the Viscosity Index. Most of the component manufacturers demand specific viscosity and viscosity index for a given application or the specific component. Viscosity index is a measure of fluid's viscosity in regard to temperature change. Thus, considering the application and the working environment users should consider both parameters.




*Picture 7. Viscosity stability aspects of a fluid /16/*

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

Too high or too low viscosity readings may be due to the presence of an incorrect lubricant, mechanical shearing of the oil and/or the viscosity index improver, oil oxidation, antifreeze contamination, or an influence by fuel contamination, air contamination, refrigerant or solvent contamination. Limits for changes in the viscosity depend on the type of lubricant being analyzed but most often have a marginal limit of approximately 10% and a critical limit of approximately 20% higher or lower than the intended viscosity /17/. Therefore by measuring viscosity trend (rise/fall) system failure can be prevented, but a further analysis of root cause must be done, which ofcourse takes time.

Another method is seen by measuring Total acid number (TAN) or base number. Acid number and base number tests are similar but are used to interpret different lubricant and contaminant-related questions. In an oil analysis test, the acid number is the concentration of acids in the oil, while the base number is the reserve of alkalinity in the oil/17/. Acid number that is too high or low may be the result of oil oxidation, incorrect oil or additive depletion. Oil oxidation can be linked to water rise in the system, because water accelerates oil oxidation, which is also one of the reasons of viscosity rise.

Taking into account zinc dialkyldithiophosphate (ZDDP), additive that improves antiwear (AW) properties of the oil, can deplete and cause oil film to breakdown afterwhich metal-to-metal contact will occur at high pressures. Besides, ZDDP also has a role as antioxidant, corrosion inhibitor, viscosity improver, extreme pressure additive (EP) and detergent /18/. Therefore, viscosity changes within the systems are linked to additive depletion also. Finally, consideration of the external factors that may interfere with the operability and fluid condition which may eventually compromise the performance should be addressed while seeking to solutions to this issue as also alluded by /20/. A critical factor of internal and external temperature may not be addressed while using other parameters such as wear sufficiently, hence parameters like viscosity which is directly affected by temperature may offer the best fit to address this aspect.

## *CONCLUSION*

Firstly and foremost, this research was done to drawthe attention of maintenance personnel and system userson the importance of condition based maintenance and monitoring techniques. Authors of the paper presented the types of contamination in hydraulic systems, and agree that particle contamination is the most damaging onein the sense of causing wear of hydraulic components. However, other types of contamination (especially water) are influencing the degradation of physico-chemical characteristics of the oil. In response to that, different type of monitoring techniques and on-line instruments should be used.

Noticing the fact that rise of particles within the system are used as pre-warning sign of failure is disputable, therefore integrating monitoring of other parameters is advanced. If one consideres the rise of water content in the fluid as a pre-warning that failure or wear in the system may occur, the same could be used as an early signal. Although authors emphasize and agree that particles may still rise in the system if the hydraulic machinery is working in an adverse environment. The same goes for poor sealing, detaching the system for maintenance, etc, which leaves the system open for particles ingression.

Since the industry 4.0 is demanding real-time data measurement,it is good to use data from signal processing and trend analysis like on-line instruments (APCs, flow, temperature, pressure, etc) but authors also propose using instruments for measuring viscosity and/or water presence/19/ in early detection by viscometers and trend analysis performed agaiinst thresholds. In order for oil analysis report to be effective authors advocate that limits and thresholds for trend analysis of online measurement should be confirmed or combined with off-line laboratory diagnostics. In that way results can be more accurate and reliable to not only assist in maintenance decision making but also for future development and improvement of maintenance monitoring technique.

Another important thing to point out, while performing on-line measurements in order to acquire real-time data, engineer or technician must not use only data from trend analysis of one specific measurement in terms of data, but rather focus on more inter-related parameters using prediction modeling to reduce risk of failure or system stoppage.

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

## *LITERATURE*

/1/ Battat, B. & Babcock, W., (2003), Understanding and reducing the effects of contamination on hydraulic fluids and systems., The Amptiac Quarerly, Vol. 7, Num. 1, pp.11-15.

/2/ Frith, R.H., and Scott, W., (1993), Control of solids contamination in hydraulic systems – An overview, Wear, Vol.165, pp.69-74.

/3/ Wakiru, J.,Pintelon, L., Chemweno, P., Muchiri, P., (2017) Analysis of lubrication oil contamination by fuel dilution with application of cluster analysis. 17th International Conference on Industrial Systems (IS'17). Novi Sad, Serbi, October 2017. pp.252-257.

/4/ Hydraulic solutions (2016). Part 2: Contamination in Hydraulic Systems, Available at: <http://hydraulicsolution.com/2016/11/14/part-2-contamination-hydraulic-systems/> 14.11.2016. Accessed [03.05.2018].

/5/ Ng, F., Harding, J.A., Glass, J., (2017). Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring. Mechanical Systems and Signal Processing, Vol. 83. pp.176-193.

/6/ Herman, M. Pentek, T. Otto, B. Design principles for Industrie 4.0 scenarios. 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, 2016, pp. 3928-3937.

/7/ Ng, F., Harding, J.A., Glass, J., (2017) Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring. Mechanical Systems and Signal Processing, vol. 83, pp.176-193

/8/ E.C.Fitch., (1988), Fluid Contamination Control., Stillwater, OK 74075., FES Inc. USA.

/9/ Tič, V. & Lovrec, D. (2017), On-line condition monitoring and evaluation of remaining useful lifetime for mineral hydraulic and turbine oils, University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia.

/10/ Lovrec, D. & Tič, V. (2012). On-line condition monitoring systems for hydraulic machines. Facta Universitatis Series: Mechanical Engineering. Vol. 10., No.1., pp.81-89.

/11/ Kühl Andreas. Condition Monitoring – many options, one goal. Proceedings of OilDoc 2011 conference. Rosenheim, Germany, 2011.

/12/ Tic, V., Lovrec, D., Edler, J., Operation and Accuracy of Particle Counters for Online Condition Monitoring of Hydraulic Oils, Annals of Faculty Engineering Hunedoara – International Journal of Engineering, Vol. 10, Iss. 3, pp.425-228.

/13/ Eaton Vickers, (2002), The systematic approach to contamination control: A complete guide for maximum system performance, Eaton Corporation, Document No. 561, USA.

/14/ Glavač, D. (2017), With Hydac on the way to Industrie 4.0: Industrie 4.0 based predictive maintenance, International Fluid Power 2017 Conference, University of Maribor, Maribor, Slovenia, pp.31-40.

/15/ Murrenhoff, H.: Condition – Monitoring of Hydraulic Drives and its Fluids, Proceedings Fluidnatehnika/Fluid Power 2005, p.p. 141 – 161, Maribor.

/16/ Fitch, E.C., (1992), Proactive Maintenance for Mechanical Systems, Elsevier Advanced Technology, Stillwater, OK, USA.

/17/ Fitch, B., (2013), Anatomy of an oil analysis report, Machinerylubrication, Available: http://www.machinerylubrication.com/Read/29598/oil-analysis-report, Accessed: 05.05.2018.

/18/ Spikes, H. (2004), The history and mechanisms of ZDDP, Tribology letters, Vol. 17, No. 3, pp.469-489.

/19/ Nan, X., Haibo, Z., Shenyong, G., Yan, M., Weimin, C., (2009), Development of online measuring instrument for water-in-oil percentage based on MCU, International Forum on Information Technology and Applications, IEEE. pp.563-565.

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs

/20/ J. Wakiru, L. Pintelon, P. Chemweno, P. Muchiri, A lubricant condition monitoring approach for maintenance decision support - a data exploratory case study, in: Maint. Forum, 2017: pp. 69–82.

*Teaching Asssistant, Department of Industrial Engineering and Management, Faculty of Technical Sciences
orosnjak@uns.ac.rs