Applying contamination control for improved prognostics and health management of hydraulic systems

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Abstract. Contamination control is one of the most critical methodologies in preserving the integrity of hydraulic systems. Besides contamination controls' contribution in achieving higher reliability and efficient energy utilisation, it also enables flexible and precise motion control of actuators. Therefore, in conducting condition-based maintenance (CBM), contamination control must be considered as an integral part of the same maintenance policy. To fill these gap authors firstly extracted all the relevant information of the current state-of-the-art research, discussed the drawbacks within current oil contamination control procedures, and proposed an adequate prognosis and health management approach for oil condition monitoring. In that sense, the authors used a rapid literature review based on Cochrane's systematic review guidelines. The literature shows that most of the studies are focused on filter management techniques. However, neglecting oil degradation could lead to the inadequate prognosis of the system operational state. Therefore, the authors analysed a real-case agricultural tractor and additionally monitored parameters like viscosity, pour point, flash, and spectrometric analysis, besides using conventional automatic particle counter (APC) for oil monitoring. The results showed that the critical point of accelerated wear is the first 300 hours of agricultural tractor operation. The underlying reason is that silicon particles are an instigator of surface degradation, consequently, influence the rise of ferrous and copper particles. With the increase of wear within components (e.g. pump, and valve), the flow increases, pressure-demand, temperature, vibration, leaks, etc. In that regard, energy consumption is higher, which, even without a failure, causes a production loss. Based on the results, the authors suggest that future research should be more dedicated to energy-based maintenance (EBM) in terms of maintaining quality and assessment of reliability.

Keywords: Contamination Control, Rapid Review, Condition-Based Maintenance, Regression Analysis, Prognostics and Health Management, Energy-Based Maintenance.

Introduction

Hydraulic fluid directly affects system operational performance in regulating motion and force applied at actuators. Hence, the hydraulic fluid should be considered as one of the most critical components of the system, if not the most important. Failures in a hydraulic system are usually related to oil contamination, where up to 70% of these failures are related to solid particle contamination[1–6]. Therefore, to perform designed tasks, the hydraulic fluid must suit appropriately for the desired application, must be clean, and must be adequately maintained. To accomplish aforementioned a subfield in hydraulic system maintenance, namely contamination control, is responsible for maintaining the cleanliness of the fluid. Oklahoma State University, directed by Ernest C. Fitch[7–11], is mostly responsible for coining the term and states that contamination control:

"…*is a broad subject and applies to all types of material systems, and is concerned with planning, organising, managing, and implementing all activities required to determine, achieve and maintain a specified contamination level*".

Accordingly, contamination control includes all systems involving interacting elements, both material (working and transgressed substances) and energy (stored and transitional). Unlike other authors that are dealing with oil contamination, Fitch divides contaminants into two areas: material and energy. However, most of the research currently is dedicates to physical contaminants. Contamination control became so popular that it led to the development of standards, namely, Contamination Control (ISO/TC 131/SC 6). There is currently 34 published standards and six standards under development.

The importance of contamination control in hydraulic systems is seen through better dynamics, lower internal leakage, and higher energy utilisation. Maintaining fluid cleanliness is becoming more demanding due to increased precision of component clearances (e.g., pumps and servo-valves). Today, contamination control plays a crucial role in the hydraulic system and is considered as an integral part of Condition-Based Maintenance (CBM) policy [4,12]. Work by prof. Stecki [5] reflects the importance of contamination control encompassing proactive and predictive maintenance as diagnostic and prognostic aspects, which was later on shaped as aspects of CBM program by prof. Jardine [13].

The aim of this paper is twofold. Firstly, to carry out a systematic review and to contribute to the current body of knowledge regarding research of contamination control enrolled in practical case studies. Secondly, to perform a case study taking into account actual state-of-the-art methodologies of hydraulic fluid analysis.

The rest of the paper is as follows. Section 2 includes a literature review based on Cochrane systematic review guidelines, namely Rapid Review (RR). This review contains a detailed explanation of every step performed as a systematic approach, meaning that other authors can replicate it with almost the same outcome. Chapter 3 represents the methods and materials used in the research, while the results of oil analysis are presented within the section. Chapter 4 describes a detailed review and discussion of the results emphasising the importance and dichotomy of studies synthesised in chapter 2. Chapter 5 provides a research contribution to the literature, research limitations, and concluding remarks.

Literature review

A literature review is conducted on an evidence-based approach (EBA)[14], namely Rapid Review, motivated by the systematic literature review guidelines[15–17]. Rapid Reviews are conducted in a systematic manner. However, they differ from the systematic literature reviews (SLRs) in the sense that one author can review all the

papers included and in a shorter period due to time limitation. The need for this review is motivated by the implications and the lack of contamination control approach in practical case studies. Therefore, the first research question is defined as:
RQ1: What is the current state-of-the-art research of hydraulic fluid contamination control performed on actual case studies?
From the first research question, the authors consider that vital information are methods and procedures employed, as well as instruments and sensors used for oil analysis. The need for this information is reflected in the discrepancies between laboratory conditions and the practical applications of such systems. Therefore, the authors propose additional research questions:
RQ2: What are the methods and procedures applied to determine oil cleanliness and particle generation?
RQ3: What are the most common instruments used for hydraulic oil analysis?
Based on the research questions, the authors used boolean operators combined with keywords given in **Error! Not a valid bookmark self-reference.** for the following databases: Web of Science (WoS), EBSCOhost, and SCOPUS.

Table 1. Keywords and strings used for database search

Search string	WoS	EBSCO	Scopus
"hydraulic system" AND "contamination control"	5 (5*)	616 (21*)	197 (61*)
"hydraulic system" AND "oil cleanliness"	1 (0*)	185 (10*)	20 (6*)
"hydraulic system" AND "solid particles"	3 (3*)	1457 (91*)	121 (71*)
After Exclusion NR criteria	8	17	54
After Exclusion LR criteria	1	5	13 (-3**)
Removing duplicates			-4
TOTAL			12

*After inclusion criteria

**Papers with no access

For articles to be included in the research, they must fulfil all of the inclusion and exclusion (I/E) criteria, which are explained in detailed and given by Table 2. Inclusion and exclusion criteria.

Table 2. Inclusion and exclusion criteria

I/E Criteria	Subcriteria	
Inclusion criteria	Full-text papers (FTP)	Selected studies that are only abstracts, presentations, or posters will not be included in the study.
	Language (LAN)	Full text of the article must be written in English.
	Time frame (TF)	Selected studies must be between 01.01.2009 - 31.03.2019 to be included in the review process.

	Non selected studies (NSS)	Studies included must be peer-reviewed (e.g., journal articles, conference publications, dissertations, chaptered. books, monographs).
Exclusion criteria	Non-related (NR)	NR1: Studies that are only referencing the problem of contamination. NR2. Studies that are not dealing with hydraulic fluid.
	Loosely related (LR)	LR1: Studies that are not dealing with particle contamination. LR2: Studies not providing the data of oil analysis (e.g., particle counting, elemental analysis, wear analysis, etc.). LR3: Studies that are dealing with practical case studies of machines employing hydraulic control systems.

Flowchart of rapid review

Rapid review process described by the diagram in Fig. **1** is conducted in two phases: screening phase (I) and the in-depth analysis phase (II). The first phase includes two steps: 1. Reading the titles, abstracts, and keywords, and evaluating whether or not the paper should be accepted based on the inclusion criteria (FTP, LAN, TF, NSS). 2. Applying the first exclusion criteria (NR1 and NR2).

The second phase includes an extensive review of the remaining papers, based on the second exclusion criteria LR (LR1, LR2, and LR3). Besides, all three authors must reach a consensus on whether the paper should be included in the database.

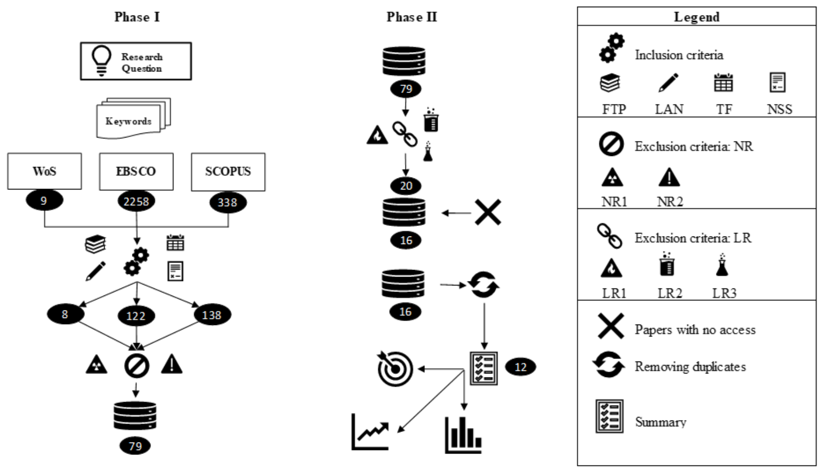

Fig. 1. Rapid literature review flowchart

Articles included in the studies by year

Results showed only journal articles (9) and conference papers (4). The rest of the results were excluded due to exclusion criteria (NR and LR). The results also showed that no studies were conducted from 2009 to 2010, and the articles were also missing in 2015. Even though there are a vast number of papers before LR criteria (79 studies), which shows that research is lacking practical examples, meaning that most of the research was performed in the laboratory.

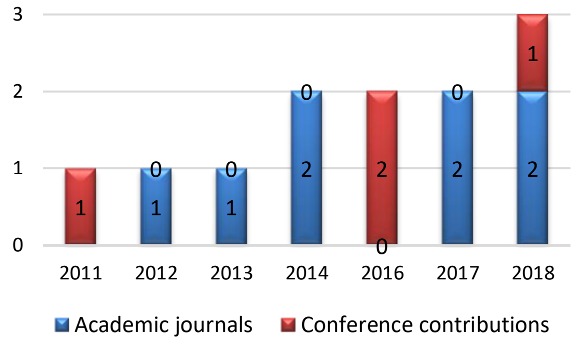

Fig. 2. Type of research articles by year

Research analysis

The vast majority of studies relates to the influence of contamination on components such as pumps and directional valves (**Error! Reference source not found.**). Even though pollution is mainly associated with preserving the most sensitive elements within the system, articles are also emphasizing the importance of filter management.

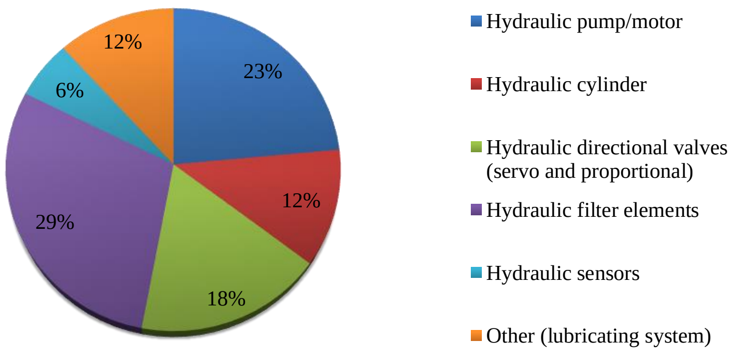

Fig. 3. Hydraulic components analysed or discussed in the study

Applying appropriate contamination control methodology includes necessary instruments for prognosis and health management of a system. Although most of the articles include only automatic particle counters (APC) (**Error! Reference source not found.**), which is insufficient. The underlying reason for this is that the oil with the same ISO 4406:17 class does not necessarily have the same effects on, for example, wear (e.g. hardness of Si and Fe particles). From the elemental analysis of the same oil

ISO 4406:17 class can be seen that one or the other oil sample can have lower or higher levels of hard solid particles (ferrous), hence, causing intensive wear of components.

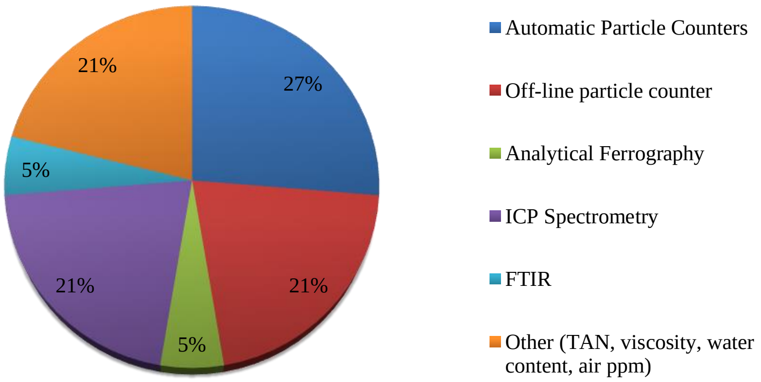

Fig. 4. Instruments used for oil analysis

Description of literature review

Literature analysis concerned with contamination control is mostly dedicated to the influence of solid particles and filter management. Zeng and Li[18] applied the contamination model on a heavy construction machine to determine the effectiveness of contamination prediction. The model is based on contamination balance approach proposed by Fitch[6], where results showed an error of ±200 counts per ml, which is a relatively good result, taking into account that authors performed research on an actual case study and not in controlled laboratory conditions. Gareyev et al.[19] used image theory to construct a tree graph of condition changes of hydraulic fluid with different concentration of contaminants. The model is used as a basis for prognosis and system control within the aircraft CBM. However, the model only advisable with the usage of in-line and on-line instruments with the lowest methodological inaccuracy of oil cleanliness. Although, Gareyev et al. emphasized that on-line and in-line particle counter can be an effective method used for CBM, Ng et al.[20] disagree, emphasising that dynamic data extracted from in-line particle sensors are still not sufficiently detailed to be used as a successful prediction method. Besides, Ng et al. also emphasise that the main focus is monitoring copper and ferrous particles (e.g., pumps and valves). Even though discussed examples emphasize the oil analysis of the whole system, others propose addressing prediction models on a specific component. For example, Wang et al.[21] researched aviation piston pump to determine the remaining useful life (RUL) of the pump. With the contaminant-based life prediction model they proposed, the life expectancy can be almost identical as designed life. However, in their research, they only used the influence of solid particles. Zhang et al.[1] went a step further, including the impact of water and gaseous contaminants on the life of the aviation system. Additionally, they emphasised that applied purification filtering can reduce solid particles above 98,4%, maintain gas solubility below 2%, and water content below 50 ppm. Jocanović et al.[2] investigated the impact of inappropriate positioning of the filter that leads to failure, mostly abrasive wear. Besides, Jocanović et al. also proposed economic analysis showing that poor design and inadequate filtering can reduce annual income by 5%. Similarly, Li[22] analysed the case of servo-valves; however, with no filter in the system. The results showed progressive wear mostly due to the fast erosion of throttle edges of the valve.

Most of the studies are emphasising the importance of filtration. Singh et al.[23] addressed this question specifically by proposing a Contamination Management System (CMS). The CMS system involves monitoring the various parameters like viscosity, temperature, and contamination level. They applied FMEA analysis where RPNs (Risk Priority Numbers) showed that pump, pressure filter, and proportional valves are the most critical components. To address these issues, they propose implementation of appropriate filter elements, descant type breathers, and wiper seals leading to improved reliability, economy, and service life of the system. Machal et al.[24] proposed that off-line filtration is better for the hydraulic system than in-line filtration. The results showed reduced wear particle concentration (Fe, Cu, Si, Al, Ni, Mo, and Cr) while preserving the level of additives within the system (Ca, P, Zn). Majdan et al.[25] further investigated the study of biodegradable hydraulic oils with the usage of off-line filtration. In their first study [25] they showed that off-line filtration could help reduce ferrous metals and particles above 14 microns. On the second study[26] they used comparative analysis of implemented filters at three locations – external filtration, the output of the hydraulic pump, and tractor-implemented filtration. The results also showed that external filtration is most useful to reduce pollution while preserving the level of additives. The underlying reason for their research is to prolong oil replacement since biodegradable oils are more expensive than usual mineral oils. Karanović et al. [27] conducted a lubricant oil analysis (LOA) program as a support for maintenance-decision making to determine optimal replacement period for hydraulic oil. Monitoring parameters in their study included TAN, viscosity, water content, and particle counts, and the results showed as superior data helping maintenance managers to conduct more independent decisions rather than strictly following manufacturers recommendations.

Literature review shows that most of the studies are addressing the influence of solid particles and elemental analysis; however, there is evident lack of studies regarding the impact of gaseous and water contaminants on system performance. On the other side, the effects of pollutants, such as gaseous and water presence, can and will affect the performance of the system. Hence, the lack of oil monitoring data such as TAN and viscosity content can be misleading while conducting PHM within the CBM policy. Therefore, authors are taking into account the data above in PHM of the system, since they present multiple interrelated factors while proposing the remaining useful life (RUL) of the system and the oil. From the research questions, it is noticed that only a few authors are including physicochemical analysis of oil, while others conduct only particle counts within their prognosis. Additionally, most of the studies are lacking some statistical analysis to compare different parameters of oil. Authors wish to include multiple different factors with regression analysis and to draw attention to the influence between various oil properties for a better system diagnostics.

Materials and methods

The case study was conducted on agricultural tractor CASE Magnum using hydraulic UTTO tractor oil. The analysis is conducted over 1310 engine hours, under working conditions. Each of the parameters is monitored and analysed according to standards for different oil properties. Parameters of oil that are monitored are the following: viscosity (40°C and 100°C), viscosity index, flame point, pour point, particle count, and elemental particle analysis.

Results of oil analysis

Viscosity, flame and pour point, and viscosity index are measured by off-line laboratory according to standards and guidelines for conducting analysis. The oil used for oil analysis is extracted via a minimess valve. However, particle counts are done via automatic particle counter (APC). Elemental analysis was performed using Wavelength Dispersive X-ray Fluorescence (WDXRF) spectrometry. Although the literature shows the usage of ICP spectrometry, authors conducted WDXRF spectrometry analysis due to availability. Additionally, the advantage of WDXRF analysis over ICP is of higher sensitivity to larger particles and simple sample preparation[28]. However, comparing to other studies, results can vary significantly, depending on the instrument.

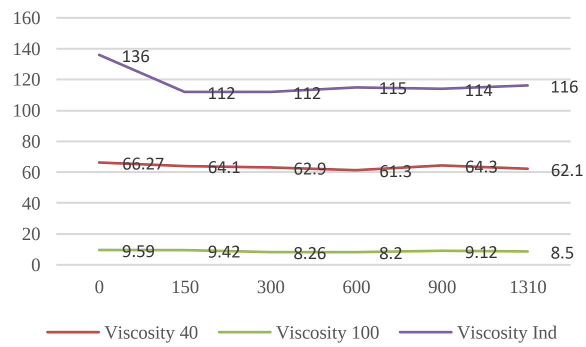

Fig. 5. Viscosity analysis

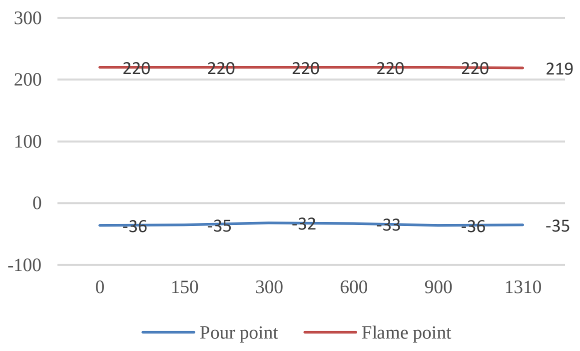

Fig. 6. Pour point and flame point

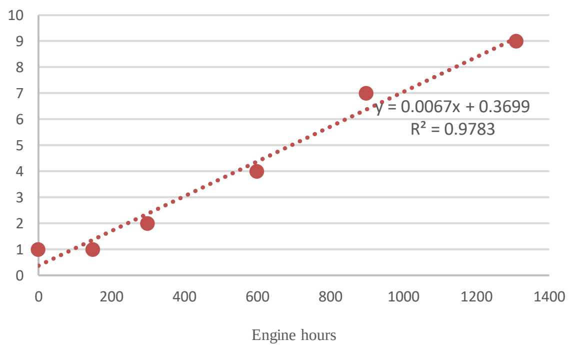

Fig. 7. Copper content

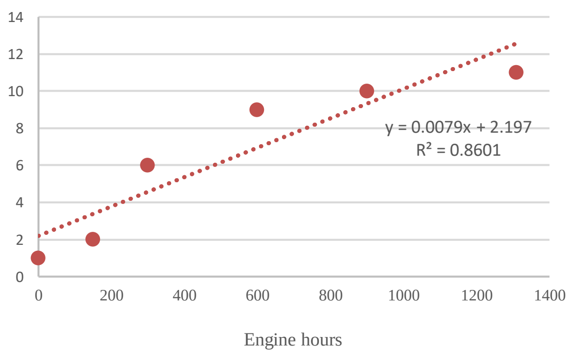

Fig. 8. Iron content

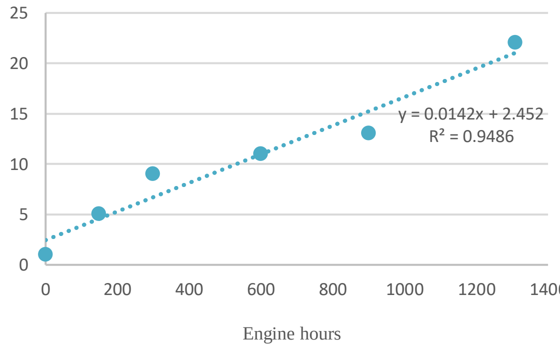

Fig. 9. Silicon content

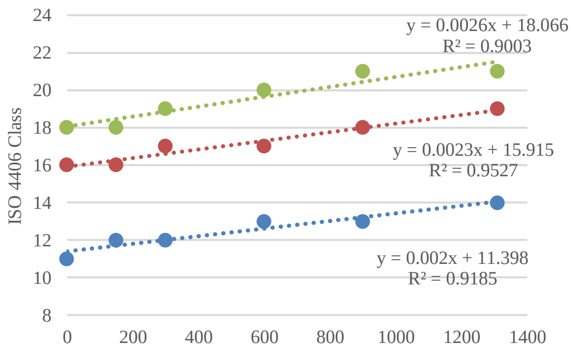

Fig. 10. ISO 4406:17 Class level measured by a particle counter

Discussion

From the data derived from oil analysis it remains unclear how did oil viscosity index had a massive drop from the starting point to 150 hours (Fig. 5**Error! Reference source not found.**), but drastic viscosity drop was not noticed during the system exploitation. The prediction could be various: mixing the oil with coolant, water entrance, sample contamination during storage and preparation, etc. However, the viscosity index did not change until the final sample of 1310 hours, where viscosity at 100°C dropped below ±10% where the oil should be replaced.

Even though Singh et al.[23] emphasised that solid particles (insoluble ones) pose the greatest threat. In addition, the authors emphasise that particularly ferrous particles are the greatest threat that could lead to wear increase. However, the results show that Si particles are the starting point of wear (Fig. 9), leading to increase of ferrous particles that take the leading role on increased wear (Fig. 8) and higher wear intensity process, which can lead to failure or jamming the component (e.g., valve sticking). All of the results showed a linear increase of solid particles with WDXRF elemental analysis

(approx. R^2=95%), except ferrous particles that show R^2=86% accuracy, i.e., the proportion of variance. Authors conclude that once the wear started, it will continue the wear process even though filtering was performed adequately.
Additionally, authors also included measurements of water content analysis with WDXRF, and results showed that water content was below 0,05% after final sample. However, some recommend that water content should be below 0,03%. Therefore, FTIR analysis could also be included to check the chemical composition of oil and to see how it affects oil degradation. Authors included a much broader spectrum of oil analysis in a practical case study of tractor UTTO oil where data used is better for prognosis and health management of the system. Additionally, Zhang [1] proposed vacuum centrifuge to reduce solid particles, air, and water; and results showed lower energy dissipation to heat and friction. Hence, more research should be dedicated to lowering the intrusion of air and water into the hydraulic system.

Conclusion

Contribution to the literature

This research is one of the first papers in the sphere of contamination control of a hydraulic system that systematically addressed the literature. Additionally, it seems that the existing body of knowledge of contamination control is by no means mature, and lack of practical case studies is evident. Besides, literature analysis shows that most of the articles rely on particle counts; however, exact shape, type, and particle size distribution (PSD) lacks in the literature. The results also show the need for more sophisticated particle counters, since widely used APC based on light scattering method (with ISO4406:17) do not include measurement of particles below <4 microns, and more research must address the impact of small particles on system wear. Oil analysis in this study showed that silicon particles cause internal component wear and accelerate wear due to the increase of Fe particles after 300 hours. Therefore, particle counters that measure metallic particles could provide much more benefit to diagnosis than traditional APCs.

Research limitations

Limitations are seen twofold. Firstly, while conducting a case study, the measurements of various environmental temperatures were not included. Since the temperature can affect oil physiochemical degradation, the authors propose that the measures of heat must be included within the prognosis of the system. Secondly, the authors consider that measurements of PSD by more sophisticated instruments or manual particle counts by microscope method (ISO 4407) must exist. The underlying reason for this is that APC usually mistakes air and water droplets for solid particles during measurements, leading to a deviation in results. Therefore, the need for more sophisticated measuring techniques is more than evident.

Closing remarks and future research

From the literature analysis, few research gaps are noticed. Firstly, wear influences increase of clearances within the hydraulic components, hence, influencing the increase of flow, leaks, and higher pressure requirement. In that sense, the question of how does this phenomena, within the maintenance approach, influences energy waste is not researched so far by authors knowledge. Therefore, how does contamination affect overall energy consumption must be addressed. For example, wearing of the pump will lead to lower power utilisation, hence higher energy demand. Besides, authors also highlight the lack of studies regarding oil degradation due to temperature. Therefore, technological research should be dedicated to the invention of instruments that could conduct particle counts with additional properties such as shape and element type. The devices should also be designed as online instruments because offline laboratory analysis used today consume a tremendous amount of money and time.

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