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Innovative Approach to Cleaning and Cleanliness Control of Newly Manufactured Hydraulic Assemblies

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Abstract.

Initial cleanliness of hydraulic components is vital for system reliability and longevity. Existing on-line oil condition monitoring technologies, though advanced, cannot verify baseline cleanliness before assembly. To address this limitation, a novel device was developed that combines component flushing and cleanliness evaluation in a single process. The system features a dual-pump configuration: one pump performs high-flow flushing and sampling, while the other circulates and filters a glycol-water fluid. Flow is controlled through valves, and contaminants are collected under vacuum onto membrane filters for microscopic evaluation per ISO 4407 and rated using ISO 4406. A key innovation is vibration-assisted flushing, which effectively dislodges embedded particles. Tests showed cleanliness improvements of 3–5 ISO codes within five minutes. The device provides a practical, repeatable, and ISO-compliant solution for verifying initial hydraulic cleanliness, with planned developments including automated particle analysis and integration into digital quality management systems.

Keywords. Cleanliness, membrane filters, IS0 4406, ISO 4407, filtration, particles.

2. INTRODUCTION

Ensuring the cleanliness of hydraulic components prior to assembly is crucial for system reliability, wear prevention, and extended operational life. Contaminants such as metal particles, dust, or residues from manufacturing can cause premature wear, clog valves, and reduce the efficiency of hydraulic systems, making initial cleanliness a key determinant of long-term performance.

Particles that are in the fluid can cause abrasive wear [1,2] and cause damage to surfaces. For instance degradation of hydraulic gear pump is shown in increase of microparticles in the fluid, which causes a decrease in the quality of the fluid, which is a class that does not meet the prescribed standards. Solid particles cause specific wear mechanisms of the contact surfaces (abrasion, erosion, material fatigue, etc.) [3,4]. Karanović et al. [3] describe the influence of solid particle impurities in the radial gap between the control piston and the directional valve housing: due to three-body abrasion, they carry away material and increase the gap. As the gap increases, the flow through the gap also increases (internal leakage), which causes even more particles to travel through the gap. This further increases friction and stimulates the wear process. Pressure losses in the gaps and friction of the particles cause local heating. Optimal fluid cleanliness is required to reduce the intensity of wear. Jung-Hun et al. [5] studied the influence of particle composition and particle quantity. It is proven that size distribution also have an impact on damaging the surfaces because that are so-called “critical size” particles [6,7], that come between two surfaces, causing three body abrasion. This phenomenon is also shown in tribological studies in micro-scale abrasive tests [8].

Fiber filtration technology is used due to its versatility, adaptability and superior filtration efficiency [9]. Multilayer nonwoven fiber filter media has superior flirtation efficiency, lower pressure drop and higher dust holding capacity [10,11]. The filtration velocity and fiber diameter along with surface energy determines the pressure drop through filter material [9].

Although real-time, on-line oil condition monitoring has seen rapid advances in recent years—supported by sensor fusion, microfluidic technologies, and inductive-resistive detection systems [12–14] —these systems are inherently limited in their ability to assess the initial cleanliness of hydraulic assemblies. On-line particle counters are most effective during early system operation but quickly lose relevance as contaminants either settle or disperse. This limitation makes it particularly difficult to verify the baseline cleanliness of components immediately after manufacturing, creating a gap in quality assurance processes.

Current standard practices for cleanliness assessment rely heavily on manual sampling and laboratory analysis, which can be time-consuming, subjective, and insufficiently integrated with the cleaning process. Furthermore, complex geometries within hydraulic assemblies often trap particles in hard-to-reach areas, reducing the effectiveness of traditional flushing or filtration methods. To address these challenges, there is a need for a methodology that combines efficient cleaning with objective, reproducible measurement of particulate contamination. Integrating vibration-assisted flushing with ISO-compliant membrane filtration and microscopic particle counting for measuring cleanliness offers a promising approach to overcome these limitations. The purpose of this paper is to critically evaluate such a methodology for cleaning hydraulic pipe assemblies and to demonstrate its effectiveness in achieving the required cleanliness standards, providing a reliable and repeatable workflow for pre-assembly quality assurance.

3. MATERIALS AND METHODS

The objective of the developed device is to provide a repeatable procedure for achieving and verifying the required cleanliness level of pipe assemblies (PA) prior to their integration into hydraulic systems. To reach this goal, the device combines controlled flushing, vibration-assisted particle excitation, and standardized cleanliness measurement within a single workflow. Cleanliness verification is performed by sampling contaminants onto membrane filters using a vacuum filtration unit, followed by microscopic analysis in accordance with ISO 4407 [15] and cleanliness classification according to ISO 4406 [16]. This approach enables both effective removal of contaminants and reliable assessment of the resulting cleanliness level.

The working principle of the device is based on two hydraulically separated but functionally complementary circuits, driven by two electric motors and centrifugal pumps. The first circuit is dedicated to flushing and cleanliness measurement of the PA, while the second circuit continuously filters the working fluid to maintain a stable and low background contamination level. A glycol–water mixture (DOWFROST™ LC 25) is used as the flushing medium due to its suitable viscosity, corrosion protection, and thermal stability.

3.1. Flushing function and performing cleanliness measurements

The device consists of a centrifugal pump (MovitecV 006/11) which pushes the liquid through the throttle, further along the flexible pipe to the upper ball valve and further to the pipe assembly. The liquid flows through the lower ball, through the coarse filter (25 µm) and the fine filter (3 µm) into the tank. The flow rate is determined by the centrifugal pump characteristics and the overall pressure drop of the system. A throttle valve was used to modify the system resistance (control the pressure) and thus flow rate. At full throttle opening, the pump outlet pressure was 6.7 bar and the flow rate was 150 L/min, whereas at an outlet pressure of 9.2 bar (with semi-closed throttle) the flow rate decreased to 50 L/min. Pressure was measured at the pump outlet and therefore does not directly represent the pressure drop across the pipe assemblies, which remains constant for a fixed configuration and is governed by pipe dimensions and quick couplings. Pump maximum pressure is 11 bar. In case of higher pressure-resistance pump will not provide flow because of the limitations of centrifugal pump. The viscosity decrease due to the increase of temperature is negligible.

In the case of performing cleanliness measurements, the upper ball valve is bypassed, so that the vent filter is in function. The liquid passes through the quick coupling to the PA via the bypassed lower ball valve and the measuring tube to the measuring ball valve and the vacuum device for separating particles on the membrane. The measuring ball valve supplies the appropriate volume of liquid (100 ml) to the upper container of the vacuum device for separating particles on the membrane, which must be provided for the cleanliness measurement.

3.2. Liquid filtration function and heating

The second circuit also contains a centrifugal pump, which sucks the liquid from the bottom of the tank and pushes the liquid through flexible pipes via a fine filter (3 µm) into the tank. This circuit is intended exclusively for filtration and maintaining a high level of liquid cleanliness.

A heater is located in the tank, for heating the liquid in the tank. The temperature switch and the level switch constitute a safety module that switches off the entire device if the liquid has a higher temperature than that set on the temperature switch or if the liquid level is lower than the minimum permissible level (determined by the float mounted on the level switch in the tank). The vibration motor (Netter Vibration NEG 5050 Electric-vibrator, external 400V, 3000 rpm) is important in vibrating the pipe assembly during the flushing function and is controlled by a frequency regulator mounted in the electrical cabinet. Vibration is defined as the applied mechanical oscillation of the system, quantified by its frequency (Hz). The frequency converter may regulate the frequency between 20 and 60 Hz at a constant torque load (linear volt-hertz-curve). It was set to 40 Hz (stage 7 out of 14 on frequency potentiometer control rolling button).

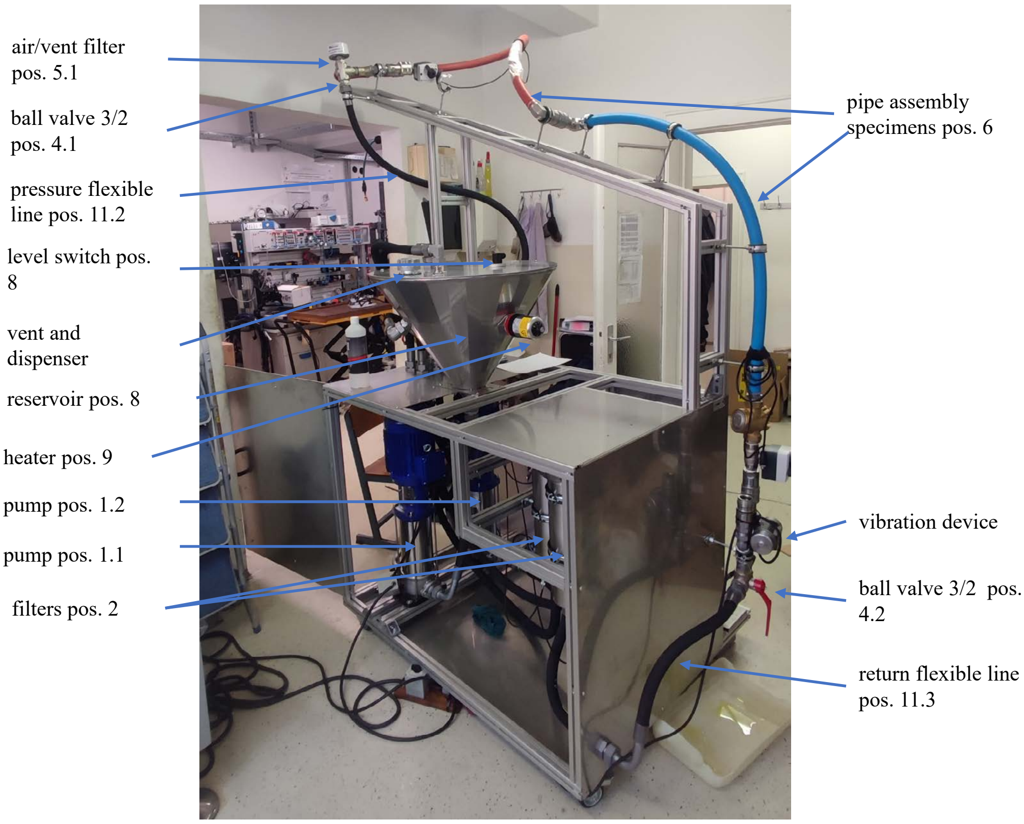


Figure 1. Test rig for cleaning and performing cleanliness measurements on pipe assemblies (PA)

Table 1. Hydraulic scheme (Figure 2) of components BOM

Position	Description	Position	Description
1	centrifugal pumps	8	tank
2	fine filters 3 µm	9	heater
3	coarse filters 25 µm	10	throttle valve
4	3/2 directional ball valve	11	flexible lines
5	breather filter 3µm	12	thermostat
6	pipe assembly (PA)	13	level switch
7	laboratory accessories	14	quick couplings

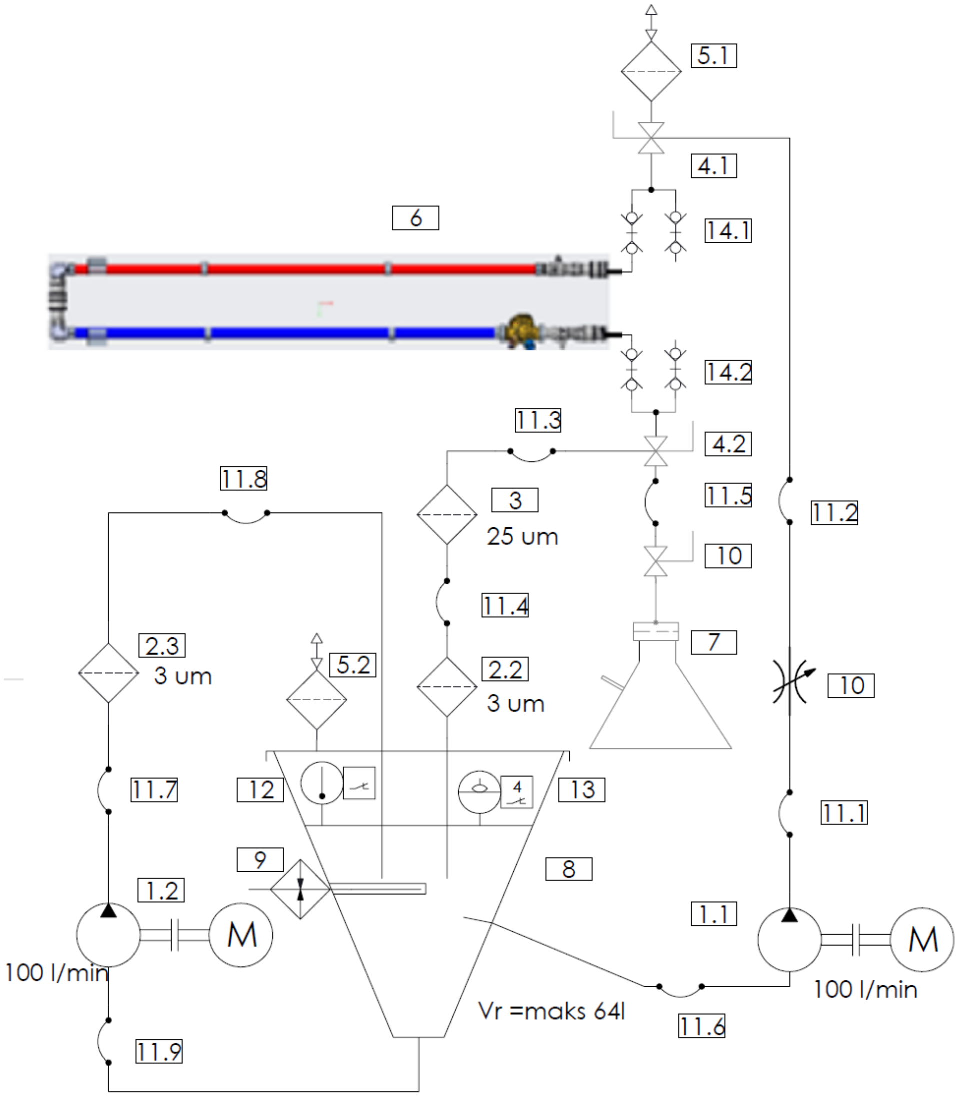


Figure 2. Hydraulic scheme of cleaning device for PAs

3.3. Procedure for flushing and measuring cleanliness

The cleaning and cleanliness assessment of pipe assemblies (PAs) were performed using a dedicated device integrating controlled fluid flow, vibration excitation, and membrane filtration. Prior to measurement, the hydraulic connections were configured so that the lower 3/2 ball valve established a link between the PA and the measuring tube, while the upper 3/2 valve connected the supply line to the PA. The assembly was mounted using quick couplings to ensure a sealed, contamination-free connection.

To define the initial liquid volume, the pump was actuated intermittently, introducing approximately 1600 ml of glycol–water mixture into the PA. A one-minute vibration cycle was applied to release loosely bound contaminants. The flow path was then redirected toward the vent filter to enable sampling. Cleanliness evaluation was conducted by vacuum-filtering 100 ml of the working fluid through a membrane, capturing suspended particles for microscopic examination according to ISO 4407. Multiple samples were taken to ensure statistical reliability.

Following the initial measurements, the rinsing/flushing phase start by redirecting the flow between the PA, inlet, and outlet lines. The rinsing pump was operated for approximately five minutes, accompanied by vibration excitation to enhance particle removal from internal surfaces. After rinsing, the flow configuration was restored for sampling, and the cleanliness measurement was repeated under identical conditions.

Upon completion, the PA could be disconnected either filled with fluid or vented, depending on subsequent handling requirements. This procedure provides a repeatable method for both cleaning and ISO-compliant cleanliness verification of hydraulic pipe assemblies, enabling a quantitative assessment of contamination removal efficiency.

Test coolant DOWFROST LC 25 with fluorescent yellow-green colour was used. It can be diluted with water. The liquid also supports bio-oxidative degradation at concentration between 15 % and 25 % glycol volume. Viscosity of fluid is 2.5 mm^2/s at 20 °C and 1.5 mm^2/s at 50 °C. In Table 2 there are given characteristics of the liquid [17].

Table 2. Characteristics of DOWFROST LC 25 [17]

Component	**Concentration**
Water	65.0 – < 75.0 %*
Propylene glycol	> 25.0 – < 26.0 %
Dipotassium hydrogen phosphate	1.0 – < 5.0 %*
Sodium tolyltriazole	≥ 0.1 – < 0.25 %*

Initial cleanliness, measured from the plastic container was 14/14/12. Temperature was varying from room temperature due to the insufficient cooling system and at times reached temperature up to 100 °C.

3.4. Measurements according to ISO 4407

Solid particle contamination in hydraulic fluids was quantified following ISO 4407, which specifies a standardized microscopic counting procedure for determining fluid cleanliness. Maintaining low particulate levels is critical for the operational reliability of hydraulic systems. Although the method was once constrained by manual counting and slow analysis, recent progress in automated microscopy and digital imaging has re-established it as an efficient and accurate technique for contamination assessment.

For all cleanliness evaluations, 100 ml of DOWFROST LC 25 working fluid was vacuum-filtered through a membrane to collect particulate contaminants released from the pipe assembly (PA). The initial cleanliness, referred to as pouring, was determined by introducing clean fluid into the PA through short pump cycles, followed by one minute of vibration excitation. The resulting 100 ml sample was withdrawn and filtered through a membrane. Subsequent measurements were performed after different flushing periods, where highest cleanliness improvements were observed. During filtration, the membrane filter was carefully positioned on the vacuum apparatus to prevent airborne contamination (figure 3). The upper container was secured with metal clips, clamping the membrane between the container and the porous support.

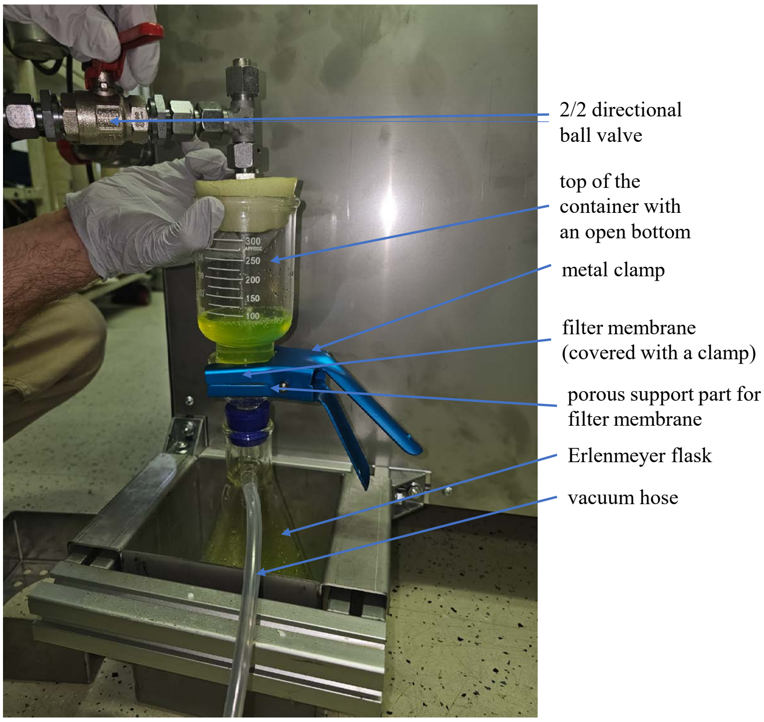
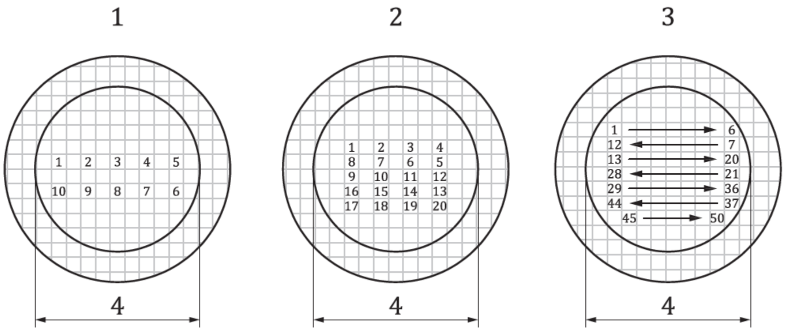


Figure 3. Taking a sample of the cleanliness of the liquid on a vacuum device for membrane filtration

A 100 ml fluid sample was introduced through the measuring tube and filtered under vacuum. After filtration, the membrane was removed with its holder and prepared for analysis. Samples were then placed in an oven at 50–60 °C for two hours to ensure uniform drying without thermal damage. The dried membranes were subsequently examined under a microscope to determine particle count and size distribution in accordance with ISO 4407.

In Figure 4, the number 4 indicates the effective diameter through which the liquid is filtered. The filter membranes are Φ47 mm in size. The first set of filters was made of mixed cellulose (MCE) material with 0.45 μm pores and 2.69 mm x 2.69 mm squares etched into the membrane. The second set of membranes was made of the same material with 1.2 μm pores without squares.



Key

1	10 squares
2	20 squares
3	50 squares
4	effective filtration diameter of membrane

Figure 4. Particle counting in 10 area squares using method 1 according to ISO 4407 [15]

The number of particles was determined in 100 ml of liquid according to the ISO 4407 standard using the equation (2.1) [15]:

$$N = \frac{A \cdot n \cdot 10^5}{f \cdot L \cdot W \cdot V} \quad \text{in 100 ml} \qquad (2.1)$$

where:

A [mm^2] effective filtration area

n [/] number of counted particles larger than the selected size

f [/] number of counted squares

L [mm] length of the observed rectangle, or mesh size

W [µm] width of the observed rectangle,

V [mL] volume of filtered liquid

After drying the membranes, the particles were examined under a Nikon Eclipse Ti-U microscope (Japan) equipped with an IDS u-Eye camera for classical transmitted light technique. It allows for combination with an EMCCD Andor Ixon 888 Ultra camera, a Carin Optosplit III image splitter system and a CoolLed pE-4000 illumination source for epifluorescence microscopy. Only classical transmitted light technique with an E Plan 10X/0.25 objective and WD 7.0 was used.

Since an area of 1 mm x 1 mm was imaged due to magnification and the standard states that the entire square area is analysed, it was necessary to take several images and then combine them in the Image J program and appropriately determine the particle analysis field [18]. This was followed by determining the particle detection intensity threshold, since the analysis works on the bitmap principle and the program counts automatically. The program allows for measurement of the Feret length, which is described in more detail in the article by Walton [19]. Count and classification were done for the Feret particle lengths in Excel into size categories specified by ISO 4406. The oil cleanliness rating consists of three numbers, the first indicating the class of particles greater than 4 μm, the second the class of particles greater than 6 μm, and the third the class of particles greater than 14 μm per milliliter of liquid.

4. RESULTS AND DISCUSSION

The fluid cleanliness was measured based on the filtration of 100 ml of DOWFROST LC 25. The results were divided into 3 sets. The first set presents the cleanliness measurements of the flow pipe assembly (blue) labelled PA1F and the return pipe assembly (red) labelled PA1R at the beginning before rinsing (pouring) and after different flushing time intervals.

The second set presents the measurements of the combined flow-return pipe assembly labelled PA2FR and determines the cleanliness for both pipe assemblies simultaneously. The cleanliness results are presented at the beginning before rinsing (pouring) and after different flushing time intervals. The last set presents the results of the combined flow-return pipe assembly sets labelled PA5FR and PA6FR using the same procedure with slight changes in regard to vibrations and flow.

4.1. Determining cleanliness measurement from particle counting method

The procedure for determining cleanliness measurement by microscopic particle counting and translation to ISO 4406 is shown using the example of a PA1F pipe assembly. Figure 5 shows the beginning (pouring) before rinsing. First, an image is obtained from the microscope. Figure 6 shows the threshold setting for automatic particle detection software [20]. All red zones are recognized as particles that are determined according to the threshold, as can be seen in the box in Figure 6.

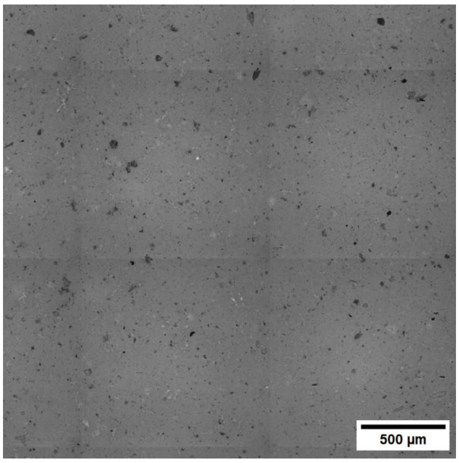


Figure 5: Particles in one particle analysis square for sample PA1F at the beginning (pouring) before rinsing

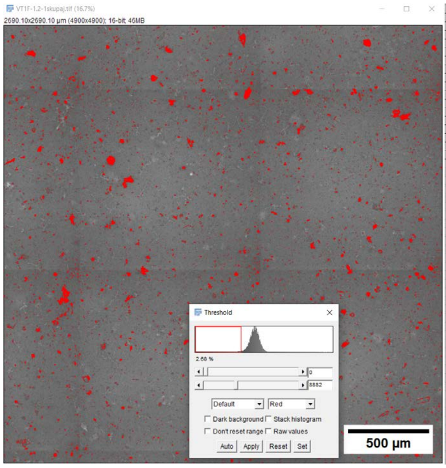


Figure 6: Determination of the particle detection threshold for the PA1F sample at the beginning (pouring) before rinsing

When a threshold is selected, the program automatically converts the image into a 2-bit image (Black and White) (Figure 7). Then it is analysed with the Analyse Particles function in Image J. In this function, it is possible to specify the values that are measured in the image [20]. The size of the particle is measured according to Feret diameter [21].

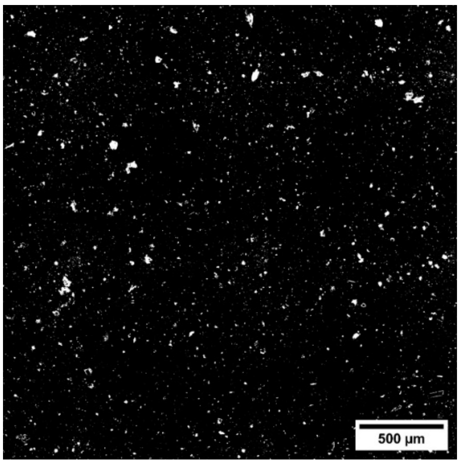


Figure 7. Bitmap for PA1F particle count analysis at the beginning (pouring) before rinsing

4.2. Cleanliness measurements

The first set of measurements served as a preliminary evaluation of the cleanliness of the hydraulic fluid itself, without the influence of any specialized cleaning procedures or treatments. For this purpose, samples from the flow pipe assembly PA1F (blue) and the return pipe assembly PA1R (red) were analysed separately. Microscopic images were obtained using MCE membranes with 0.45 µm pores, and a grid of drawn squares on the membrane facilitated systematic particle counting. This approach allowed for a detailed "blank" test, establishing a baseline of particulate contamination present in the fluid prior to any flushing. The results, summarized in Table 3, provide the largest particle detected in each of the five analysed squares, along with the corresponding number of particles per millilitre, calculated according to ISO 4406 standards. This initial assessment was essential for establishing reference values, against which the effectiveness of subsequent flushing and vibration-assisted cleaning could be quantitatively evaluated. It also allowed identification of inherent variability in particle distribution across the membrane, ensuring that later measurements would be both reliable and statistically meaningful.

Table 3: Cleanliness measurements on 5 different squares (areas) of a membrane filter of 100 ml of clean liquid (from the packaging container)

Internal	>4µm	>6µm	>14µm
0-1	28	20	2
0-2	29	22	4
0-3	98	69	15
0-4	121	91	28
0-5	71	54	33
	>4µm	>6µm	>14µm
Measured particle count 1 ml	127	93	30
ISO 4406	**14**	**14**	**12**

On PA1F measurements were performed at the beginning (pouring) and after 10 min, 20 min and 30 min of rinsing. Results after 20 min of rinsing showed high cleanliness (14/14/13) (Table 4).

Table 4: Collected together for sample PA1F according to ISO 4406

	>4µm	>6µm	>14µm	Largest particle, µm
PA1F-pouring (start)	**20**	**19**	**17**	128
PA1F-10 min	**16**	**15**	**13**	130
PA1F-20 min	**14**	**14**	**13**	87
PA1F-30 min	**14**	**13**	**11**	60

In the pipe assembly sample PA2FR, the total cleanliness of the joined "flow" and "return" pipe assemblies with quick couplings were measured at the same time. 4 repetitions of cleanliness measurements (cleanliness removal on the membrane) before rinsing (pouring (start)) and after 1 min, 2 min, 3 min, 4 min, 5 min and 27 min of rinsing (Table 5) were made (together 28 measurements). The speed of improvement of cleanliness in terms of determining the optimal time of cleaning the pipe assembly . For greater clarity, only the cleanliness according to the ISO 4406 standard is given.

Table 5: Total collected for the PA2FR sample according to ISO 4406

	>4µm	>6µm	>14µm	Largest particle, µm
PA2FR-pouring (start)	**19**	**18**	**16**	299
PA2FR-1min	**17**	**17**	**15**	295
PA2FR-2min	**16**	**15**	**11**	64
PA2FR-3min	**16**	**15**	**13**	508
PA2FR-4min	**15**	**14**	**12**	252
PA2FR-5min	**14**	**14**	**12**	113
PA2FR-27min	**14**	**13**	**11**	117

For the other samples (PA5FR pipe assembly), vibration was activated during rinsing and at the beginning, but during the actual collection of the liquid for the cleanliness measurement, the tube assembly was not vibrated. From initial cleanliness 18/17/16 the particles were reduced due to 5 min filtration to cleanliness 15/14/12. The last PA6FR pipe assembly was measured with a reduced flow rate of 50 L/min and a pressure of 9.2 bar. This measurement was made to observe the influence of the different flow rates to cleanliness and it is concluded that higher flow rates have slightly higher cleaning capabilities. The other pipe assemblies were measured with a flow rate of 150 L/min and a pressure of 6.7 bar upstream of the pump. Cleanliness went from 17/16/15 to 14/13/11 after 5 min filtration.

4.3. Examination of particles

Particles retained on the membrane from sample PA1F-pouring (start) were examined using a Hirox HRX1 optical microscope with the objective of demonstrating the capability of the proposed method to classify particle types and potential contamination sources following standardized membrane filtration. In Figure 7, an elongated red fibre was identified and measured, with a length of approximately 950 µm and a width of 20 µm. Similar fibrous particles (black, dark blue, and light blue) were repeatedly detected, indicating a systematic contamination mechanism rather than an isolated occurrence, most likely associated with tube handling or mechanical damage. Such fibres were classified as low-hardness contaminants and are therefore expected to have limited abrasive impact on hydraulic components.

A golden-yellow particle with a reflective surface was observed in Figure 8. Based on its optical appearance, this particle was categorized as a metallic fragment, potentially originating from copper-based alloys such as brass. In contrast, angular particles with dimensions of approximately 52 µm, morphologically similar to standardized test dust, were also detected. These particles were classified as potentially critical due to their sharp edges and higher likelihood of causing abrasive wear. Their presence is indicative of either airborne dust ingress, insufficient removal of sediments from the working fluid, or residual particles introduced during manufacturing processes, such as sawing or cutting operations. The identification and differentiation of these particle classes demonstrate that the examination serves not to document random particles, but to validate the method's ability to systematically detect, size, and interpret contamination relevant to hydraulic reliability.

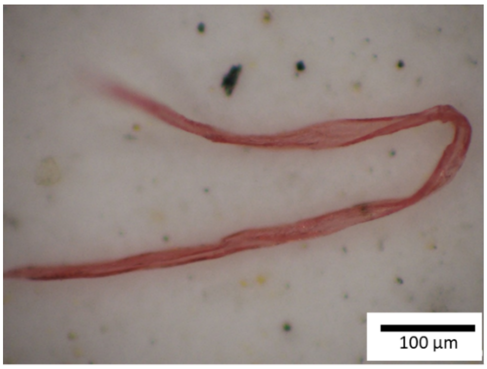


Figure 8. Red fiber on membrane pouring at 600x magnification

Figure 9. Golden-yellow particle on membrane pouring at 800x magnification

5. CONCLUSIONS

This study proposes a method for assessing and improving the initial cleanliness of hydraulic pipe assemblies that complements, rather than replaces, existing standard procedures. Conventional approaches—such as flushing and filtering with parallel use of on-line particle counters or post-flush oil sampling followed by ISO 4407 analysis—are well established and effective during system commissioning or operation. However, these methods provide limited insight into the true baseline cleanliness of newly manufactured components, as particle counters are sensitive to transient contamination and oil samples are often taken after particles have already settled or been partially removed.

The primary benefit of the proposed method lies in its systematic integration of cleaning and standardized cleanliness verification into a single, controlled workflow. By coupling defined flushing conditions with immediate, ISO-compliant membrane filtration, the method ensures that contaminants released during cleaning are directly captured and quantified. This eliminates uncertainties associated with delayed sampling, fluid dilution, or background contamination that can affect conventional flushing-and-measurement strategies.

All cleanliness evaluations are performed according to ISO 4407 and ISO 4406, ensuring full comparability with established standards. The novelty of the approach does not lie in the measurement principle itself, but in the methodological arrangement that enables reproducible, pre-assembly cleanliness verification under laboratory-like conditions. Optional mechanical excitation was introduced as an auxiliary means to enhance particle release in complex geometries; however, the core advantage of the method remains the controlled flushing and immediate, standardized assessment rather than the excitation mechanism itself.

Furthermore, the use of image-based microscopic analysis improves traceability and repeatability compared to purely manual particle evaluation, while remaining fully compliant with ISO requirements. Overall, the proposed method provides a practical and scientifically justified extension of standard cleanliness procedures, specifically targeted at the manufacturing stage. It enables manufacturers to verify and document initial component cleanliness prior to assembly, thereby closing a critical gap between production and operational monitoring. The methodology is readily transferable to other hydraulic components and can be integrated into existing quality assurance frameworks.

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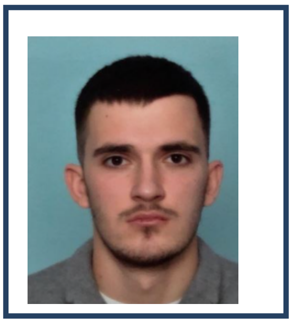

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