EFFECT OF TEMPERATURE, FLOW RATE AND CONTAMINATION ON HYDRAULIC FILTRATION

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The performance of a mechanical filter is an implicit function of many variables pertinent to fluid condition, flow variables, filter element condition and operational parameters. This paper presents the details and results of a parametric study that examined the effect of oil temperature, contamination level and flow rate on the performance of a hydraulic filter through laboratory experiments. A 5 µm rated commercial filter with glass fiber made element that had an effective surface area of 0.154 m^2 through 57 pleats was used to filter VG32 hydraulic oil. The filtrate was supplied with the contaminant of ISO medium test dust at four gravimetric levels - 2, 5, 8 and 10 mg/L of oil. The tests were conducted at the flow rates of 40 and 120 L/min for different oil viscosities, corresponding to the temperatures of 30, 40, 50 and 60^o C. As the temperature increases, the oil viscosity decreases due to weakened cohesive forces, which leads to increased filtration rates and hence more time to build the pressure, upstream of the element. On the other hand, the pressure on upstream of filter bed builds up at higher rate when the filtrate has higher level of contamination loading. An extensive investigation on the effect of flow variables and oil condition parameters on the pressure drop across the element would therefore give a better knowledge about filter element lifetime.

KEYWORDS

hydraulic filtration, temperature, flow rate, gravimetric level, pressure drop

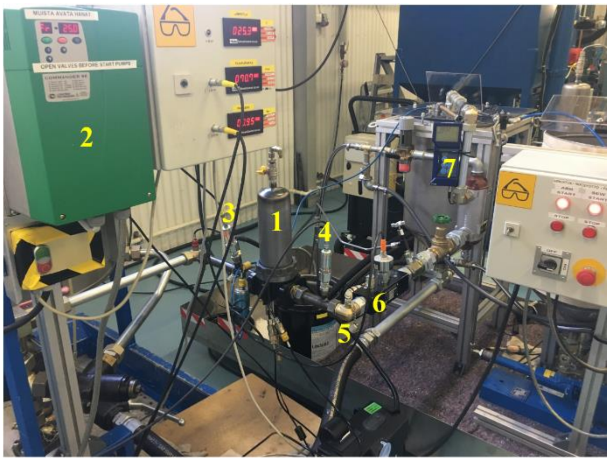
1 INTRODUCTION

Solid contamination in the lubrication oil causes premature wear of mechanical components and adversely affects their life. Maintaining a quality oil film over the solid surfaces that are under potential contact is crucial to realize the anticipated longevity of the moving parts. In addition to reduced effect of friction, an effective lubrication can decrease the temperature of the contacting surfaces, thanks to heat transfer capability. Furthermore, a quality lubrication ensures a seal between the liner wall and the segments, and keeps the internal surfaces cleaner. However, the hydraulic oil is subject to inevitable contamination, because of not only the friction between the engine components, but also the uncertain and unmatrixed environmental and operational conditions. This is usual with marine propulsion units, where the solid contamination in the hydraulic oil contains soot, sand, and metal particles. This explains the need for filtration.

Pressure drop across the porous media is the prime motivator of the oil flow through the filter. While it is usual to display an approximately linear relationship between the pressure drop across the element and clean oil flow rate, the presence of particles in the oil has an appreciable influence on the pressure difference as well as other filtration indicators (Bémer and Callé 2000; Song et al. 2007). The flow pattern, where the particles of different shapes and sizes fall in a wide range of motion regimes, and their deposition on fibrous media in the filtration applications, constitutes a multiscale physical system. The effect of particulate loading on the pressure drop across the filter element is therefore exclusive and case dependent.

Flow rate, along with throughput and degree of particle removal, is a parameter of interest in studying the filtration. The flow rate of liquids is inversely moderated by the viscosity, which in turn has an inverse relationship with temperature. Although Darcy's law gives a theoretical explanation about the effect of flow rate on the pressure drop across the porous media, this relationship exceptionally depends on the application. For example, see Lage et al. 1997; Gisinger et al. 2015; Saleh et al. 2016. The objective of this study is to characterize the oil pressure drop, ΔP, across the filter element as a function of temperature, flow rate and contaminant gravimetric level, using laboratory experiments. A test bench with a series of sensors and instruments was developed to make the empirical observations on the variations of ΔP for different filtrate properties. The trends of ΔP obtained from the experiments will be useful to develop the correlations between oil condition parameters and flow variables.

2 EXPERIMENTAL SETUP



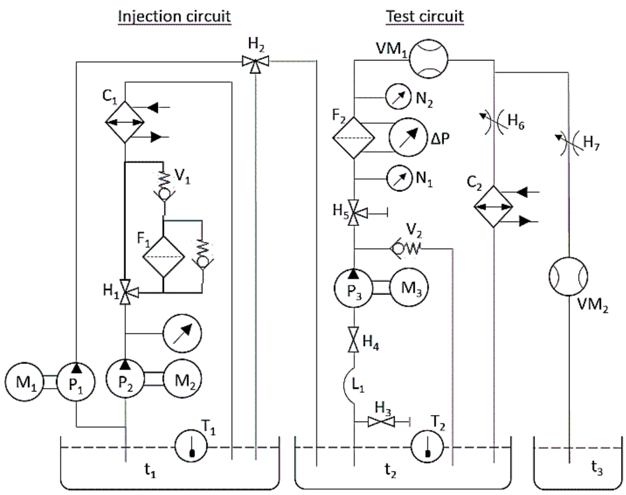
Devices
1. Filter
2. Control unit

Sensors
3. Upstream pressure sensor
4. Downstream pressure sensor
5. Particle counter
6. Flow meter
7. temperature sensor reading

Output
8. Data logger

Figure 1. Experimental setup

Figure 1 shows the laboratory test bench, developed for the parametric investigation on the hydraulic oil filtration, and Figure 2 presents the respective hydraulic network with usual notations and symbols. This network mainly consists of two circuits; one for injecting the solid contamination of medium test dust (ISO12103-1-A3) at predetermined rates, and the other for



C_1, C_2	Coolers
F_1, F_2	Cleaning and testing filters
H_1, H_2, H_5	Three-way ball valves
H_3, H_4	Two-way ball valves
H_6, H_7	Flow regulators
M_1	Gear motor (SEW EURODRIVE R32DT71D4, 0.55 kW)
M_2	AC MOTOR (ABB M2AA90L, 2.5 kW)
M_3	Gear motor (Magnetek Speed+, 3VZ132S4, 5.5 kW)
N_1, N_2	Pressure indicators
P_1	Allweiler A6 Pump (ADP 153 B21 P01, Q = 0.4-0.7 L/min)
P_2	Allweiler A6 Pump (NB 25-200/ϕ185, Q = 30 L/min)
P_3	Pump (Aktiebolaget D4F052K1)
T_1, T_2	Temperature sensors in tanks t_1 and t_2, respectively.
t_1, t_2, t_3	Tanks for particle-supply, particle-oil mixing and overflow, respectively.
V_1, V_2	Check valves
VM_1, VM_2	Flow meters (SCFT-300-32-07 of Parker and VLA-ZF03 of Kytola with 10-300 L/min and 0.1-1 L/min range, respectively)

Figure 2. Schematic diagram of hydraulic circuit (top), and explanations of symbols (bottom)

passing the contaminated oil through the test filter. A 5 µm rated commercial filter with glass fiber media having an effective surface area of 0.154 m² through 57 pleats was used as a standard test filter. ISO VG 32 oil, which has a specific gravity of 0.86 and kinematic viscosity of 32 cSt at 40° C, and 5.4 cSt at 100° C, was used as the working fluid. The positive displacement pumps were employed to deliver the specific amounts of test dust into the oil tank, and contaminated oil to the filter. The filter element was subject to a constant circulation of oil at a deterministic temperature and flow rate. The contaminant was introduced continuously until the pressure drop across the element reached a net value of 5 bar.

The sensors and instruments used on the test bench included:
- Two pressure sensors, installed on the upstream and downstream of the filter assembly
- A pressure differential sensor, to measure the pressure drop across the filter element
- Two particle counters, connected at the upstream and downstream of the filter assembly, to ensure the right amount of particle injection and unfiltered amount of contaminant, respectively
- A flowmeter, to ensure the predefined flow rate through the filter
- Temperature sensors, to measure the oil temperature in the tanks

Cleaning mode was activated after each test run in the injection and test loops to avoid the influence of the residual solids in the oil and circuit lines of previous run on the present. Care was taken to avoid leaks in the circuit and operational obstructions, and to control the flow variables related to oil condition.

3 RESULTS AND DISCUSSION

3.1 Effect of oil temperature

Viscosity is one of the critical properties of oils that determine their suitability for lubrication. Temperature has a direct influence on the oil viscosity, and hence the particle transport and filtration. In the limiting case, the lubricant may form wax at low temperatures, and undergo a rapid oxidation at high temperatures. Effect of temperature on the viscosity varies from oil to oil; the lesser the variation, the more effective to lubricate. In the present study, Cannon-Fenske routine viscometer, which is a modified Ostwald type, was used to assess the effect of temperature on the selected hydraulic oil, VG 32. Figure 3 shows the viscosity-temperature relationship. The viscosity varies between 51 and 16 cSt for the temperature range of [30º C, 60º C], with a mid-point viscosity i.e. at 40º C of 32 cSt. The filter performance was contrasted within this temperature range for two different flow rates, and corresponding pressure drop characteristics are depicted in Figure 4. Inverse relationship between the fluid viscosity and filtration rate is observed from slower rise of pressure drop across the element at higher temperature. However, this effect of temperature on the pressure rise before the element is not linear. At low flow rates, say 40 L/min, the difference between the ΔP curves at 30º C and 60º C is diverging as the element gets loaded with particles, whereas this trend is converging for the flow rate of 120 L/min. As seen from Figure 4, oil flow rate has a significant effect on the element lifetime for a given gravimetric level of solid contamination, which led us to extend the experiments to the investigation on the effect of filtrate flow rates on the pressure drop across the element during filtration.

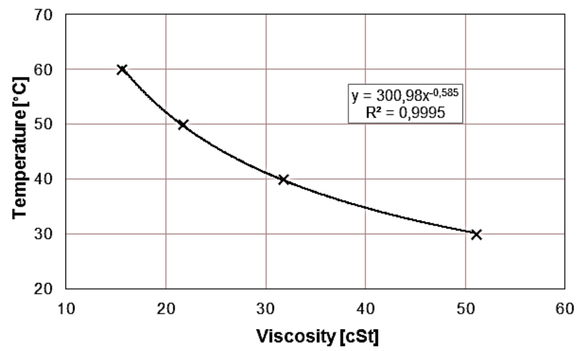


Figure 3. Viscosity change of ISO VG 32 oil with temperature

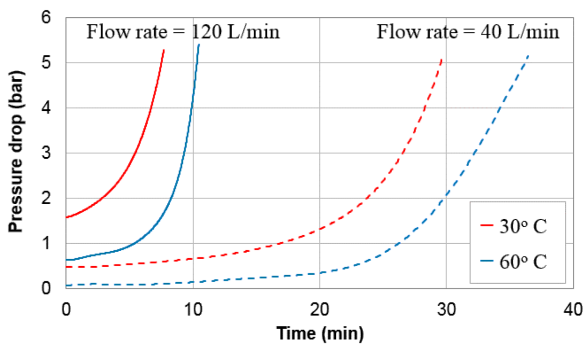


Figure 4. Effect of oil temperature on ΔP across the filter element for 10 mg/L contamination load

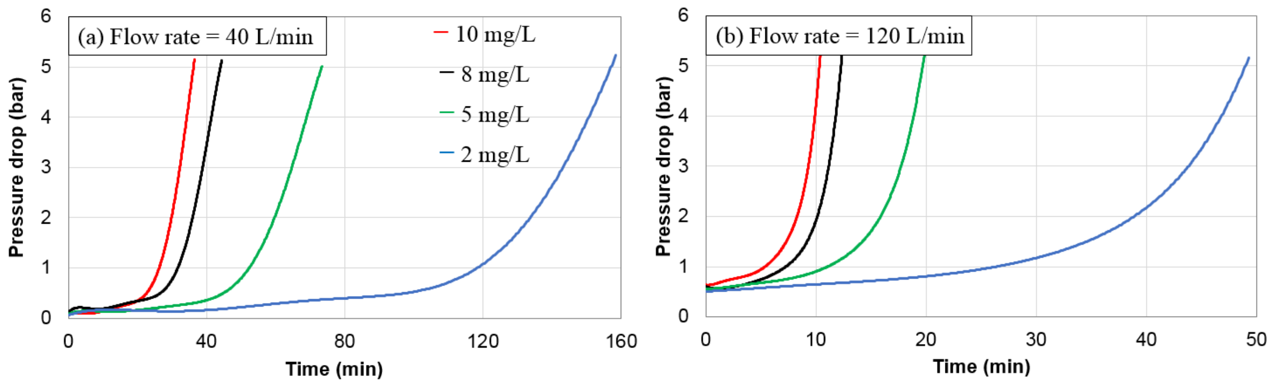


Figure 5. Pressure drop characteristics for flow rates of 40 and 120 L/min with different contamination loading at 60° C

3.2 *Effect of flow rate*

For a given solids' gravimetric level, the particles accumulate faster at higher flow rates. As a result, the pressure builds up in lesser time on the upstream side of the element, compared to the cases of low flow rates. Several statistical models are available for pressure drop across the porous media for homogeneous and heterogeneous particle accumulation (Xiao et al. 2012; Qin and Pletcher 2015). However, the complexity of practical hydraulic filtration systems with inherent uncertainties in the design and operating conditions explains the reason for paucity of similar research. In this study, the filtration was tested at two flowrates for different particle loading; 40 and 120 L/min. Corresponding pressure drop curves are plotted in Figure 5. Three major observations were made here. First, three times higher flow rate caused the pressure to rise before the element approximately three times faster. This relationship between the flow rate and pressure drop held true in all cases of contaminant loading. Second, the transition of ΔP characteristics from low-slope regime to high-slope was more gradual at higher flow rates than at lower flow rates. This explains that the characteristic time of particle accumulation is of the comparable order of time scales of flow through porous media. Finally, the contaminant loading in the oil has an appreciable effect on the filter element saturation. A linear increase in the gravimetric level of the solids does not lead to a similar trend for element clogging.

3.3 *Effect of contaminant gravimetric level*

To investigate the filtration trend of the element as a function of contamination loading, multiple gravimetric levels of test dust in the oil were used in separate tests for a given oil flow rate and temperature. Pressure difference between upstream and downstream of the element against four gravimetric levels of contaminant for a flow rate of 120 L/min is plotted in Figure 6. Although an identical trend of pressure drop is evident in all cases, there is a noticeable difference in the filter element lifetime for different particulate loading. The flow rate decreases with increasing concentration of solid particles due to increased inertial forces, which results in faster clogging of the element. Higher gravimetric levels of contaminant cause the effective flow area of the porous media to decrease, and hence a quicker pressure rise on the upstream side of the element for a given

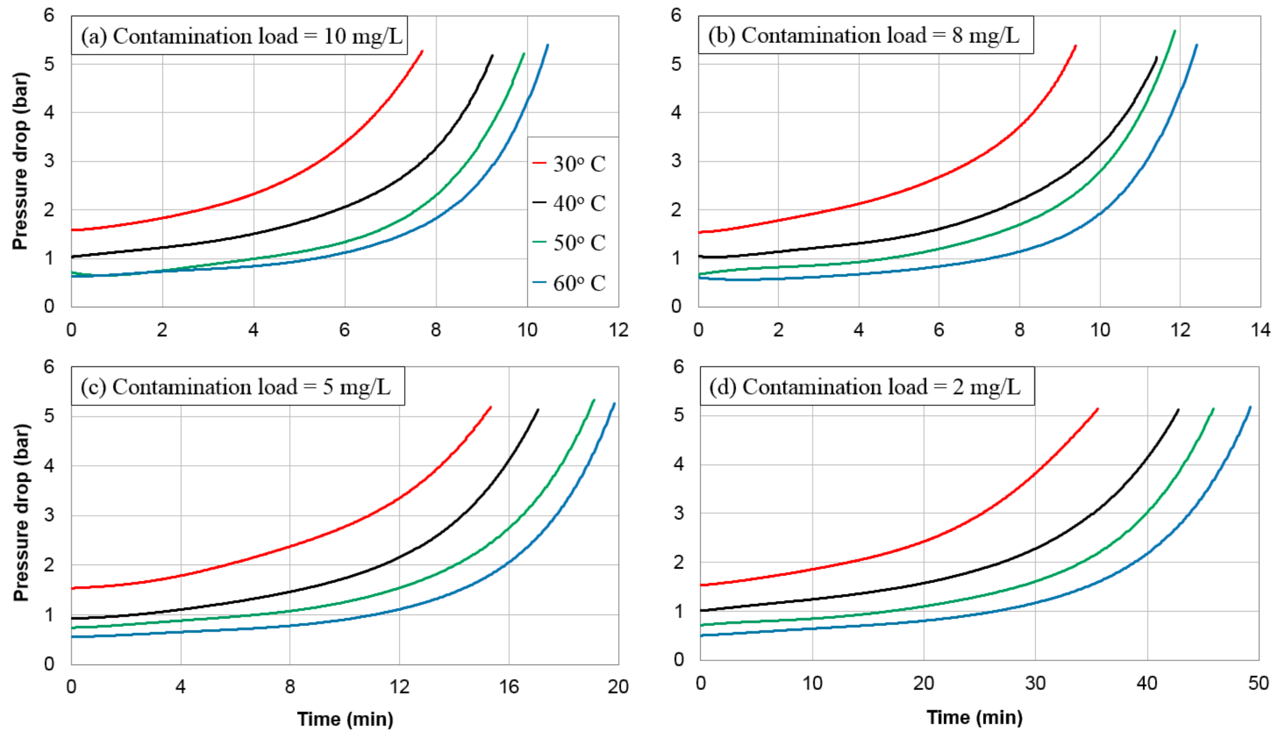


Figure 6. Effect of contamination loading on the pressure difference across the filter element at different oil temperatures at 120 L/min flow rate

flow rate. As seen from the curves, to reach the net pressure drop of 5 bar, 2 mg/L solid concentration in the oil at 60° C took nearly 49 min, which was 4.5 times of the case of 10 mg/L. Higher flow rates with higher temperature and larger particulate loading have insignificant effect on the pressure drop across the cleaner element, which is reported through the overlapping of ΔP curves at 50 and 60° C during the initial phase of filtration shows for 10 mg/L gravimetric level.

4 CONCLUSIONS

The process of filtration is associated with several complex physical phenomena, which demonstrate the interdependency of numerous fluid and solid properties. As a part of continued research on the analysis of filter element's lifetime, the present study attempted to develop the data sets that reveal the effect of different flow variables on the performance of filter element. The changes in oil temperature and therefore the viscosity affect the flow rate as well as the particles' motion. The time for the element to clog proportionally varies with the oil temperature. Increasing the oil flow rate speeds up the solids accumulation on the element. In relation to the degree of contaminant gravimetric level, the evolution of pressure drop curves is faster at high particle loading. Solid contaminants experience higher drag force as the oil viscosity increases. Further studies are under way to develop the correlations between these variables to formulate the ΔP trends to predict the element's residual lifetime.

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