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Authors

Ferrera, ML
Ades, MT
Garrido, D Sanchez
et al.

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VARNISH REMOVAL EFFICIENCY OF COMMERCIAL CLEANERS

M. Ferrera, M. Ades, D. Sanchez Garrido, A. Velasquez, D. Johnson, J. Siu, E. Montalvo, Z. Zhou, A Martini

ABSTRACT

Varnish accumulation resulting from lubricant degradation can adversely affect the efficient operation of lubricated mechanical systems. There are various chemical cleaners commercially available that claim to remove varnish, but data enabling quantitative comparisons of the performance of these cleaners is not available. Here, we used a custom test system that enables *in situ* imaging of varnish removal to directly compare nine commercially available chemical cleaners in a blinded study. Multiple qualitative and quantitative metrics were used to evaluate the performance of the cleaners. A wide range of varnish removal efficiency was observed from cleaner to cleaner, from complete varnish removal in just a few hours to almost no removal after tens of hours of testing. The results demonstrated the utility of the test rig for characterizing and measuring varnish removal and emphasized the importance of quantitative data when selecting a chemical cleaner for a given application.

INTRODUCTION

In general, varnish is a byproduct of lubricant degradation during operation that occurs primarily through oxidation of hydrocarbon molecules and can be accelerated by entrained air and water, oil contamination, mechanical stress, high temperatures, electrostatic discharge and metal particles. Lubricant oxidation is known to be the principal cause of oil degradation while in service (1,2). Varnish accumulation is also affected by the system materials, environment and the lubricant base oil and additive compositions (3-6). Varnish can accumulate on metal or wetted surfaces in a turbine lubrication system. This accumulation can lead to severe issues such as sticking of valves, increased bearing temperature, bearing failure, blockage of oil filters, and impeded heat transfer (7,8). The adverse effects of varnish are particularly problematic in areas of small tolerances such as servos and control valves. These types of failures can lead to loss of efficiency, requiring replacement of parts or, in extreme cases, catastrophic failure (9).

Varnish can be mitigated with three different approaches (10). First, as a preventive approach, lubricants with varnish control properties such as antioxidants, detergents and dispersants can be used to decrease oil oxidation and lower the varnish formation tendency (11,12). Unfortunately, improper ratios of base oil to additive or changes in operating temperature or flow rate can cause these additives to have adverse effects on varnish formation (13,14). Second, varnish and varnish precursors suspended in the oil can be removed through various types of filtration methods.

Lastly, when varnish accumulation in the system becomes severe, chemical cleaners are often the only option to remove varnish. The chemical cleaning process is conducted either through

circulating the mixture of cleaner and in-service oil under normal operational conditions of the equipment, or through external flushing often at high velocity (15). The chemical cleaners act on the surface deposits and dissolve or suspend them into the fluid. These deposits are then removed from the system by filtration and fluid drain.

A number of chemical cleaners are commercially available which claim to remove varnish from equipment such as turbines and compressors (16,17). Evaluating the effectiveness and efficiency of different chemical cleaners is challenging because there is currently no standard test method for quantifying varnish removal that enables direct comparison. To partially address this issue, a test system and method were recently developed that model cleaner flow over varnish and enabled visual tracking of the amount of varnish removed (18). In that study, the new test system was demonstrated by comparing the amount and rate of varnish removal of two chemical cleaners.

Here, we extended the investigation to evaluate nine different commercially available cleaners with test durations up to forty hours at two different flow rates. Cleaner performance was evaluated qualitatively based on pre- and post-test images of the varnish samples as well as a downstream filter that captured removed varnish particles. Cleaners were also compared quantitatively in terms of mass loss that reflected the total amount of varnish removed and analysis of images of the varnish samples taken during the removal process. The results illustrated that there were dramatic differences between the performance of various commercially available chemical cleaners and emphasized the need for standard tests to enable direct comparison and selection of the best cleaner for a given system.

METHODS

The test system was designed to enable flow of a chemical cleaner over a test coupon containing artificial varnish at controlled flow rate and temperature. A schematic of the test rig is shown in Figure 1a; detailed information about the instrument have been reported previously (18). The key feature of this set up is the test cell which houses the varnish coupon and enables *in situ* imaging of the removal process. The artificial varnish was created by reproducing oxidation mechanisms in the lab. First, a mineral base oil sample was aged per common lube oil aging tests, such as ASTM D7873 (19). In this test, 360 mL of an oil sample is heated in a test tube at 120 °C under an oxygen flow and in the presence of an iron-copper catalyst until a significant amount of sludge is formed. Then, the aged oil was filtered and sludge samples were collected. The sludge was applied to a steel coupon which was then placed in an oven for 3hr at 135°C. After baking, the varnish outside of a prescribed area in the center of the coupon was removed. This process was used to create test coupons with varnish having consistent cross-sectional area (1.5" x 0.5"). Each coupon was also massed before testing and it was confirmed that the mass of the varnish on all coupons was 76.1 +/- 4.9 mg. A photo of a representative coupon before testing is shown in Figure 1b.

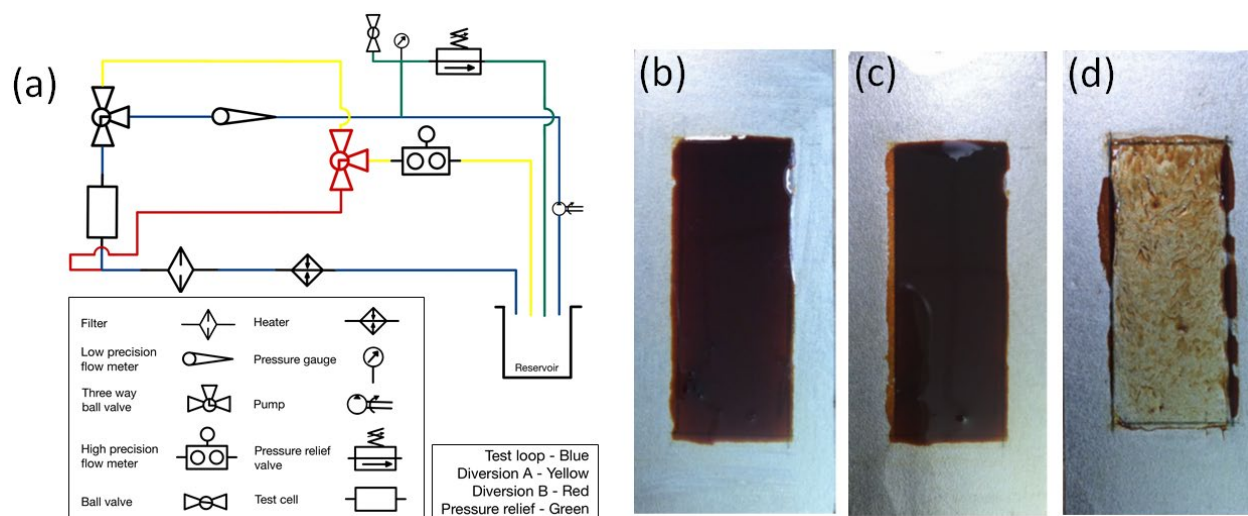


Figure 1 (a) Schematic of the test rig with key components identified. Photographs of representative test coupons with artificial varnish (b) before a varnish removal test and after 8 hours of testing with (c) base oil and (d) one of the commercial cleaner fluids.

To run a test, the apparatus was filled with new, unused cleaner fluid that was circulated and heated without passing over the test coupon until the fluid temperature reached $90^{\circ}\text{C} \pm 1^{\circ}\text{C}$. Then, the flow was diverted such that it passed through the test cell and over the varnish to begin the removal process. For the study reported here, two different flow rates were used, 0.5 GPM and 2.0 GPM. The test cell has a transparent lid which enabled time lapse photography with images taken every 10 seconds. Test durations of 4, 8 and 40 hours were used in this study. At the end of a test, the flow was stopped, and the system allowed to cool to room temperature. The coupon was removed, rotated slowly in heptane to remove excess fluid and dried in air. A representative image of a varnish coupon after testing is shown in Figure 1c. After 24 hours, the coupon was massed again to ensure all heptane was evaporated, such that the difference between the pre- and post-test masses reflected the amount of varnish removed. Next, the filter downstream of the test cell was taken out of the housing and photographed to evaluate the appearance of the removed varnish particles. Finally, the time-lapse images taken during the test were downloaded and postprocessed. The system was flushed with base oil before starting a new test to ensure no cross contamination of fluids.

Postprocessing images involved quantifying the average color of each pixel in the image in terms of the red (r), blue (b) and green (g) components of the color. The average color vector $(\hat{r}, \hat{b}, \hat{g})$ was calculated at the start of the test on both the varnish and the steel region next to the varnish. These were used as references for each test since the color and hue of the fluid itself varied from cleaner to cleaner. Then, for each image taken during the test, the average color vector of the varnish region was calculated and compared to the reference vectors. Dot products of the vectors were taken to quantify the difference between the color at a given time during the test and the reference colors. Finally, the dot products were normalized such that the varnish removal ranged from 0 to a possible 100%, where 100% would mean that the average color vector of the varnish at a given time was the same as the color vector of the steel at the start of the test.

The testing fluids, referred as C1 through C9 in this article, were made by mixing a mineral base fluid with 20 wt.% commercial cleaners in the lab. All nine cleaners were obtained from open resources. All the cleaners claim the function of removing varnish or deposits from the lubrication system in industrial equipment, by mixing and circulating with in-service lubricant at typical treat rates of 5 to 20 %. The cleaning time recommended is generally more than 24 hours. This study was blinded so as not to influence the outcome, so no details can be provided regarding the cleaner chemistry, but the comparison illustrates the variable efficacy of the current suite of cleaners.

RESULTS AND DISCUSSION

First, we performed a qualitative comparison of the cleaners based on the appearance of the coupons after tests run at a flow rate of 2.0 GPM. Photographs of the coupons after 8 hours of testing are shown in Figure 2, where the top and bottom rows correspond to images taken before and after the heptane rinse/drying process, respectively. These images indicate that some cleaners remove varnish more effectively than others. Specifically, quantitative analysis indicates that fluids C1, C2, C3, C4 and C9 removed more varnish than fluids C5, C6, C7 and C8. The photos also suggest that the different fluids remove varnish through different mechanisms. For example, while fluids C2, C3 and C4 all removed varnish, the post-test coupon images for these three cases are very different.

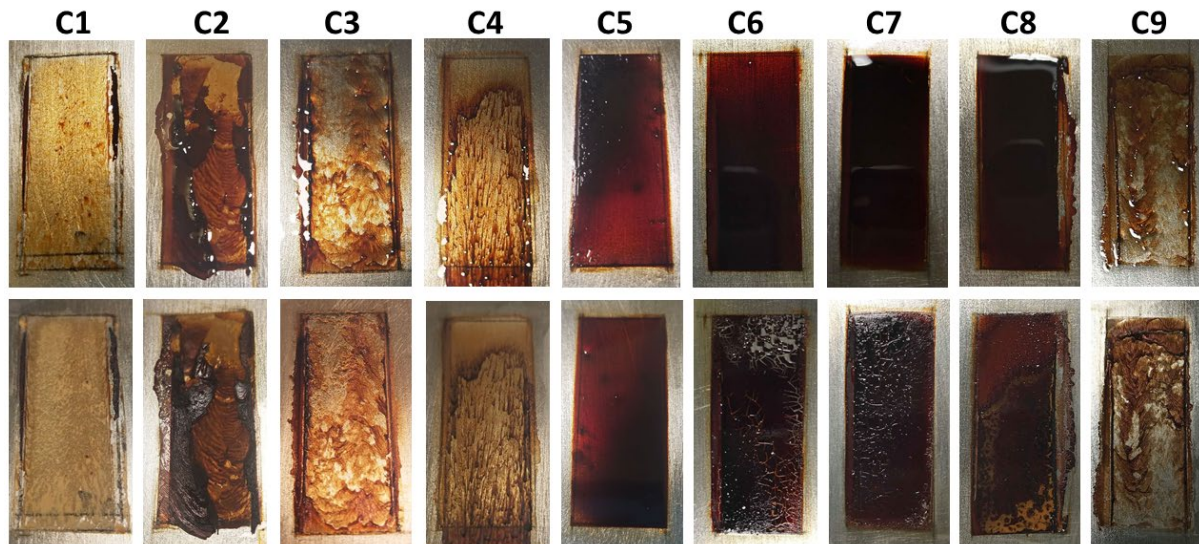


Figure 2 Photos of the varnish coupons after testing with nine commercially available cleaners run at 2 GPM for 8 hours taken before (top row) and after (bottom row) heptane rinse and drying. Fluid flow in the test cell was from top to bottom on these images.

Varnish removal can also be analyzed qualitatively based on the varnish particles collected by filter that is immediately downstream from the test cell. Photos of the filter media before and after testing with each fluid are shown in Figure 3. The filters from tests with fluids C5, C6, C7 and C8 are similar in appearance to the pre-test filter, reflecting little or no varnish removal, consistent with the observations in Figure 2. Similarly, the filter is brown for fluid C1, C2, C3,

C4 and C9 that removed more varnish in Figure 2. The filter images support the difference in removal mechanisms suggested by the post-test coupons. From Figure 3, some fluids remove the varnish in larger pieces (e.g. C2, C4 and C9) while others break the material down into smaller particles that dye the filter the color of the varnish (e.g. C1 and C3).

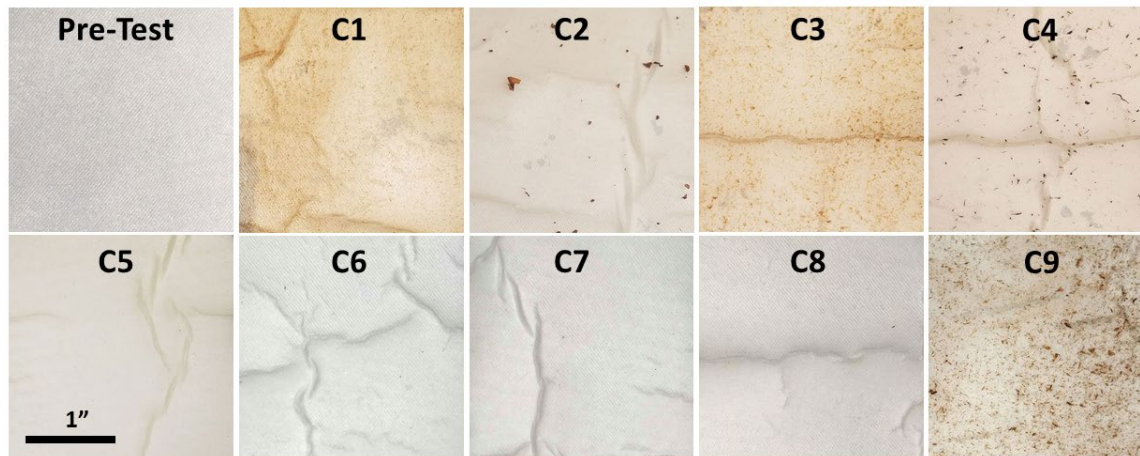


Figure 3 Photos of the downstream filter after testing with nine different commercially available cleaners run at 2 GPM for 8 hours. These images correspond to 2.5" x 2.5" squares in the center of the 3" x 5" filters. The upper left image shows a representative filter before testing.

Varnish removal can also be compared quantitatively using the difference in the mass of the coupon before and after testing. This difference was used to calculate a percent varnish removed from tests run at 2.0 GPM in 4- and 8-hour tests. The results are reported in Table 1. The percent of varnish removed as measured using this approach ranges from 7 to 95% in the 4-hour tests and 18 to 92% in the 8-hour test. However, the results also suggest that mass loss may not be an accurate approach to measuring varnish removal since, in some cases, the mass loss was greater in the 4-hour test than the 8-hour test. Comparing the mass loss from the 8-hour tests to post-test coupon photos, we observe that very little varnish was removed by fluids C5, C6, C7 and C8 in Figure 2, but the mass loss for these fluids ranged from 12% to 47% in Table 1. Since the coupons were massed after the heptane process, it is likely that the heptane process itself removed some varnish, supported by the difference between the pre- and post-heptane coupon images in Figure 2. Another limitation of the mass loss calculation is illustrated by fluid C2, for which the coupon image indicated significant removal, but the mass change was relatively small, particularly for the 4-hour test. This is likely attributable to the fact that, although the varnish was pulled away from the coupon, it clumped up and remained on the coupon, such that the change in mass from the start to the end of the test was small.

	Varnish Removal by Mass (%)	
	4-Hour Test	8-Hour Test
C1	95.0	92.0
C2	7.10	37.3
C3	51.1	52.6
C4	39.3	76.6
C5	11.6	18.3
C6	37.2	47.0
C7	32.1	31.3
C8	21.7	24.4
C9	81.3	67.6

Table 1 Varnish removed by each fluid quantified by the percent change in the mass of the test coupons before and after tests run for 4-hour or 8-hours.

Given the limitations of the mass loss approach of quantifying varnish removal, we used the coupon images taken during testing as a secondary removal metric. The results are shown in Figure 4, where lines reflect data from the 8-hour tests and shaded regions capture the difference between the first four hours of the 8-hour tests and the data taken from a 4-hour test. This shaded region therefore approximates the error associated with this test and analysis approach. Based on Figure 4, fluid C1 is the only cleaner that removed nearly all the varnish on the coupon during the 8-hour test. However, fluids C2, C3, C4 and C9 partially remove the varnish, with varnish removals between 20 and 60% after 8 hours.

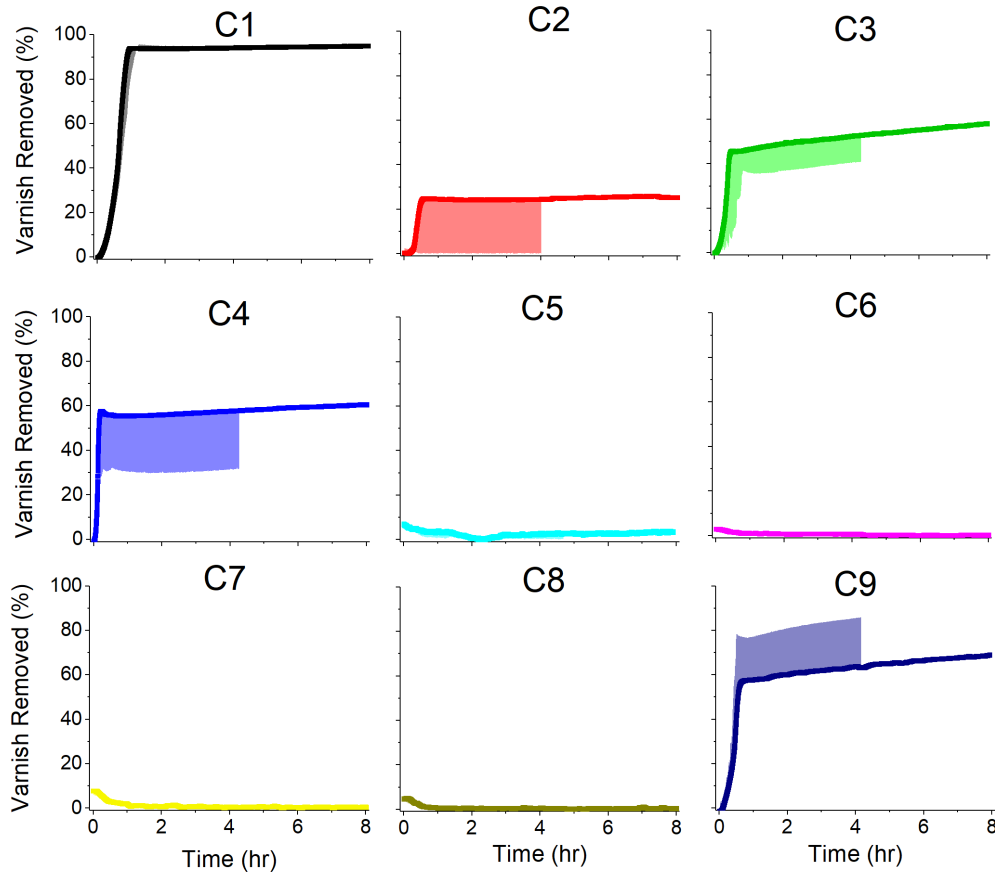


Figure 4 Varnish removal as quantified by analysis of images of the varnish coupons taken during testing at 2.0 GPM. The lines correspond to data taken from 8-hour tests while the shaded regions reflect the difference between data taken from a 4-hour test and the first four hours of the 8-hour tests.

The results of the *in situ* image analysis (Figure 4) are qualitatively consistent with the observations from the coupon and filter photos (Figures 2 and 3) as well as the mass loss calculations (Table 1). Importantly, all of these removal metrics show that C1 removes most varnish while C5, C6, C7 and C8 remove the least. However, trends are inconsistent between the removal metrics for fluids C2, C3, C4 and C9 that partially remove varnish. Differences are likely attributable to the fact that the image analysis approach is based on an average color change across the varnish region. Specifically, if the varnish clumps up or darkens during the test, the removal based on image analysis may be artificially high.

Based on the above discussion, there are limitations to both the mass-based and image-based varnish removal metrics. Therefore, to best capture the overall removal, we averaged the percent varnish removed using the mass loss and image analysis approaches from the 4-hour test and the image analysis data after 4 hours of the 8-hour test. The results are shown in Figure 5, where the error bars reflect the standard deviation across the three types of data used to calculate the average removal. These results demonstrate that the best performance was achieved with fluid C1, followed by fluid C9 and then fluids C3 and C4. The other fluids removed, on average, less

than 12% of the varnish.

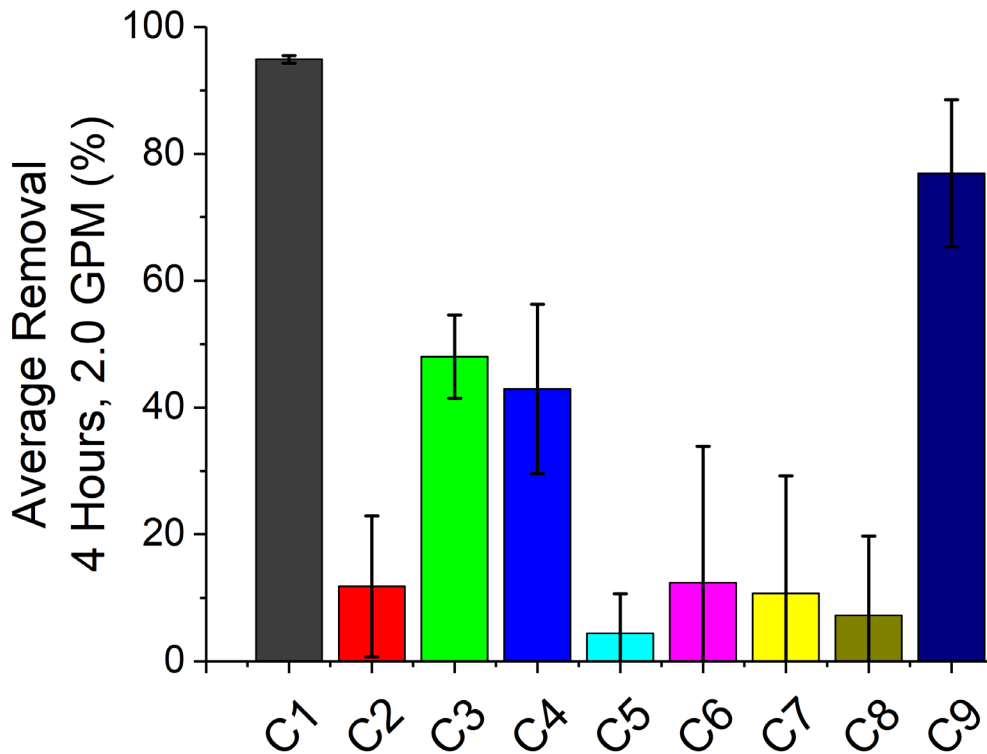


Figure 5 Percent varnish removal calculated as an average of the removal taken from a 4-hour test using both the mass loss and image analysis approaches and the first four hours of the 8-hour tests. Error bars reflect the standard deviation.

We next ran tests at a lower flow rate of 0.5 GPM with fluids C1, C2, C3, C5, C6 and C9 only, due to the limited availability of fluids C4, C7 and C8. Each test was run for at least 40 hours and fluid C3 was tested twice. The varnish removed after 40 hours at 0.5 GPM was quantified using the image analysis approach and the results are shown in Figure 6. At the lower flow rate, only fluid C1 removes any appreciable amount of varnish, with the second-best performance being observed for fluid C9 that removed 8% after 40 hours of testing. These results were confirmed by qualitative agreement with mass loss data, but the mass loss results are not shown because some tests were run for more than 40 hours so a direct comparison could not be made.

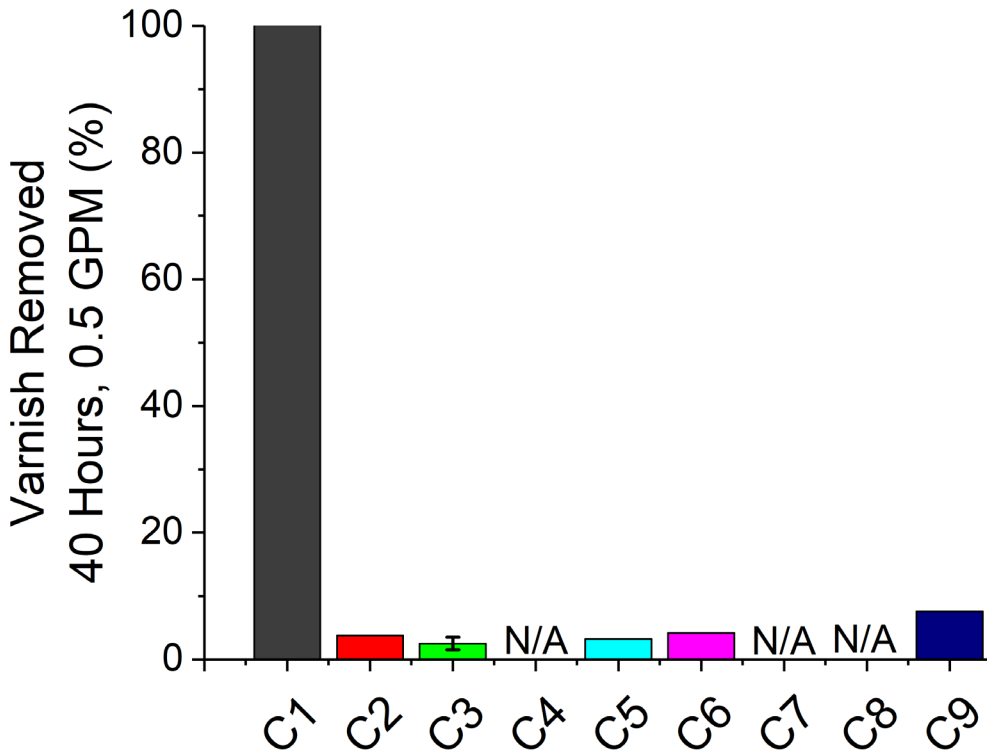


Figure 6 Percent varnish removal after 40 hours of testing at 0.5 GPM calculated using image analysis. Each test was run once, except for fluid C3 which was run twice where the difference between the two tests is reflected by an error bar for that fluid.

Lastly, we compared the varnish removal over time at 0.5 and 2.0 GPM for fluids C1, C3 and C9, the three cleaners that removed the most varnish in Figure 5. The results are shown in Figure 7. In this figure, the lines are an average of two tests for fluid C3 at both flow rates, an average of three tests for fluid C1 at both flow rates, the average of two tests for fluid C9 at 2.0 GPM and the result of a single test for fluid C9 at 0.5 GPM. Some of these tests were run for much longer, but the comparison is reported here for only the first 4 hours of all tests. The results show that varnish is removed sooner and more effectively at the faster flow rate and only fluid C1 removes an appreciable amount of varnish at 0.5 GPM. These results suggest that a higher flow rate improves the efficiency of chemical cleaners, and some cleaners cannot effectively removal varnish at a low flow rate. However, quantifying the effect of flow rate and other operating conditions is the topic of an ongoing study.

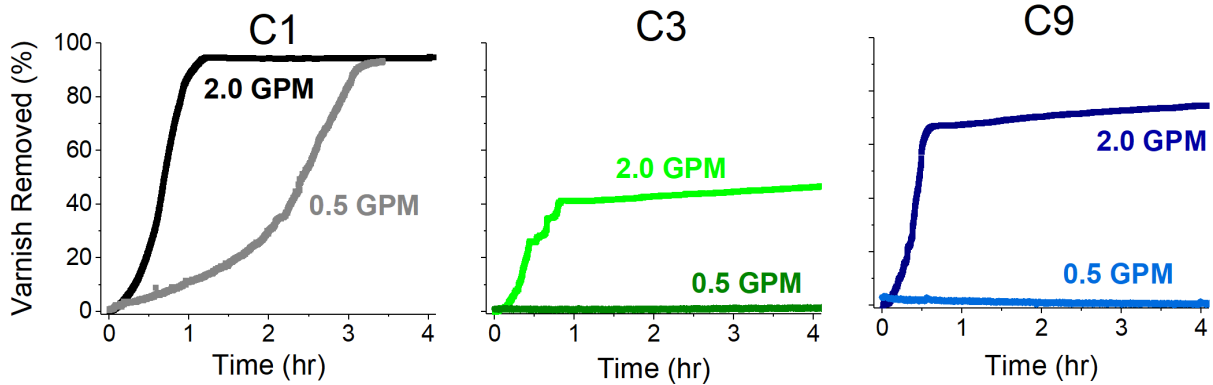


Figure 7 Percent varnish removal as a function of time for three of the best performing fluids tested at 0.5 and 2.0 GPM. Varnish is removed sooner at the faster flow rate for all three fluids, but only fluid C1 removes an appreciable amount of varnish at 0.5 GPM after 4 hours.

CONCLUSIONS

The performance of nine commercially available chemical cleaners for varnish removal was evaluated using a test system that enabled *in situ* imaging of the removal process. The images were post processed using the color of the varnish to extract a quantitative measure of varnish removal over time. Image data was complemented by qualitative analysis of the varnish coupons and the downstream filter after testing as well as measurements of the change in mass before and after the test due to varnish removal. Although all approaches of quantifying varnish removal were shown to have limitations, taken together, they enable direct comparison of the performance of the commercial cleaners.

Results demonstrate a wide range of performance is exhibited by the fluids tested, ranging from complete removal after just a few hours of testing to nearly no removal after 40 hours of testing. Further, the findings suggest that different chemical cleaners remove varnish through different mechanisms. Although we have limited information about the chemical composition of these commercial cleaners, our studies above indicate that for some cleaners, e. g. C2, the cleaner components swell and soften the varnish film, such that high speed flow is required to deform and detach the varnish film from the surface, leading to large pieces of varnish on the downstream filter. In contrast, other types of cleaners, e.g. C1, have components that break the varnish film down into small particles which can effectively be removed even under relatively low flow conditions. The direct comparison of nine commercial cleaners performed using our varnish removal test system showed that cleaner C1 has the greatest potential to reliably remove varnish from the lubrication system of industrial equipment due to its efficient varnish removal across a wide range of flow rates and less concern of removed varnish particles blocking downstream filters or valves.

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