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Comparative Performance of 12 Crankcase Oil Mist Separators

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Abstract

Closed crankcase ventilation (CCV) systems are required in most automotive markets in order to meet emissions regulations. Such systems usually require a separator to recover oil and return it to the sump. Many end users fit improved separators in order to reduce intake/aftercooler contamination with soot/oil. This study measured clean and wet pressure drop and filter capture efficiency in 12 different crankcase oil mist separators which are commonly used for either original equipment (OE) or aftermarket fitment to passenger vehicles and four-wheel drives (≤200 kW). The filters tested spanned three different size/rating classes as well as included both branded and unbranded (imitation) models. In addition to filters, separators (often termed "catch cans") and an OE cyclone separator were also examined. Testing was performed under controlled laboratory conditions using methods equivalent to previous work and current mist filter test standards. All separators were tested at flow rates between 50 and 250 lpm in both dry and "wet" (saturated with oil) states. Filtration/separation efficiency was also measured. Separators were compared based on quality factor (ratio of capture efficiency to pressure drop). A wide range of quality factors were found; however, in general, the filters were found to be superior to the catch cans, while the cyclone had the lowest quality factor. The branded filters were found to be superior in terms of quality factor, mainly due to the fact that they contained a greater quantity and/or finer separation media compared to imitation models.

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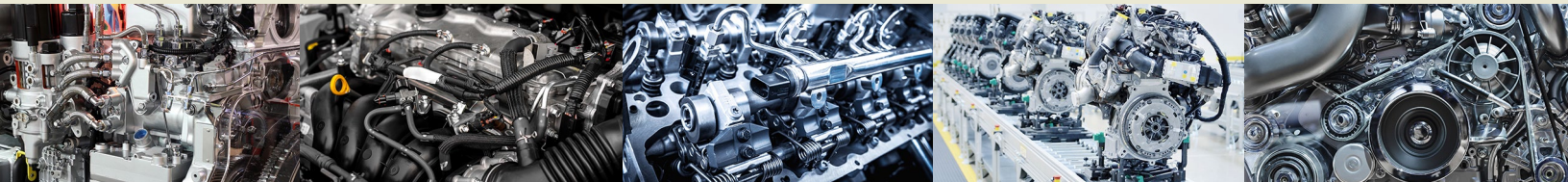
Filter, Separator, Diesel, Crankcase, Blow-by

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Introduction

Current emissions regulations in most countries consider total engine emissions, which include both crankcase and tailpipe sources. Several studies have shown that crankcase emissions from automotive engines can contribute up to 120% of the total allowable PM emissions [1, 2]; therefore, in most countries, crankcase ventilation systems have been mandated by emissions regulations for some time now [3].

During engine operation, combustion gases (so-called blow-by gases) flow between the piston rings and the cylinder sleeves into the crankcase [4]. These gases can liberate oil from the cylinder walls. The blow-by gases are composed of oil aerosol particles (0.1-10+ μm); soot particles (0.3-0.5 μm); gases, CO, CO_2, NO_x, and O_2; gaseous hydrocarbons (HC); water vapor (H_2O); and aldehydes [5]. Oil aerosol can also be produced by cooling oil sprays (piston crown cooling in heavy diesel engines). Crankcase ventilation systems are closed crankcase ventilation (CCV) and open crankcase ventilation (OCV). A CCV system filters and returns the blow-by gases to the air intake, where they are subsequently combusted, while an OCV system vents blow-by gases to the atmosphere. Several types of CCV devices exist on the market today ranging from filters, through cyclones, to simple settling chambers; however, comparative testing of such devices has rarely been performed. Contamination of the engine intake and aftercooler systems with blow-by soot/oil has been linked with reduced engine performance and premature turbocharger failure.

Some prior work exists on crankcase separator performance [6, 7, 8, 9, 10, 11, 12]. Krause et al. [10] described the procedures for measuring the ventilation aerosol on the engine. Their results indicated a significant increase in separation efficiency by using nonwoven filters. Gokten et al. [11] presented an Original Equipment (OE) crankcase ventilation and oil mist separator unit for diesel engines which was a three-layer filter element with an integrated impactor design. Gokten et al. [11] surveyed the effects of different media types, deflector and impactor designs, oil repellent chemicals, and prefilters. Their results indicated that the main root cause of oil carry-over was the transfer of oil droplets captured by the initial layer of filter media. They proposed the use of a low-density drainage layer around coalescing filter similar to that used in compressed gas cleaning applications. Kissner et al. [12] proposed two types of oil mist separators for filtering blow-by gases. These systems were an impactor with a nonwoven insert as a passive system and the electrically driven cone stack separator as an active system. According to their results, a far better level of separation was achieved in comparison with alternative systems. Bredin et al. [13] investigated the impact of oil quality on CCV filters. They found that the pressure drop across the filter correlated strongly with oil properties (especially viscosity) and increased linearly with increasing soot content in the oil. They proposed to use a combination of artificial oil aging with a discontinuous filtration method [14] to bridge the gap between laboratory bench and field filtration studies to be able to conduct "realistic" CCV tests in a laboratory. Experiments in [13, 14] were conducted using one of the filter types examined in the current work.

Several works have examined cyclones for crankcase ventilation [15, 16, 17, 18]. Cho et al. [15] performed a numerical analysis of flow characteristics and oil separation performance for a series of cyclonic oil separator designs. The results suggest that a reduction of inlet area and an increase of cone length enhance the oil separation process. In another study, Pagnozzi et al. [16] described an air/oil separation system integrated to a crankcase ventilation valve. One disadvantage in the use of cyclone separators for crankcase ventilation systems is that they have a poor separation performance for small particles (d_p < 0.1 mm) [17, 18].

Catch cans are either a "simple" or classical settling chamber with no baffles or media, however may also contain baffles or some coarse media. Recently Abilgaziyev et al. [19] studied catch can separators and optimized their design by using computational fluid dynamics (CFD). Their results indicated that efficiency would be improved when the outlet was located tangentially to the can. Furthermore, they found that droplet collection could be increased by using a longer-inner tube configuration.

Very few works present comparative efficiencies of these separators. Clearly, there is a need for studies comparing different separator systems. Such studies can provide further insights on the relative efficiencies of various separator systems. This is especially so considering the diversity of crankcase separator systems available in the market. These separator systems span a range of cost (tens to hundreds of dollars per unit), efficiency, quality, and operating/separation principle. Industry and consumers can benefit if such data is available so that they can make informed decisions regarding the use of crankcase separators in diesel engines and other systems.

Recognizing the paucity of studies that focus on comparative evaluation of crankcase separator efficiencies and quality, the present study was initiated. While a wide array of separators are available in the international market, we restricted our study to those separators readily available in the Australian market. More specifically, we focused on proprietary models used in the Australian market as well as "imitation" models. It was considered important to include such (often unbranded) imitation separators, in order to allow users to undertake cost/benefit assessments.

The current study measured both wet and clean pressure drop and also capture efficiency of 12 commonly available crankcase separators from 7 different manufacturers. Also, this study allows comparison between filters, simpler settling chamber-type separators, and OE-type cyclones.

Materials and Methods

Test Filters/Separators

Figure 1 shows the crankcase mist filters which were examined during the study. Twelve filters/separators were tested from (approximately) seven manufacturers. Filters CF1.1, CF1.5, and CF2.1 and cyclone were manufactured by MANN+HUMMEL GmbH. Filter CF1.2 is Flashlube-branded product; filters CF1.3, CF1.4, CF2.2, and CF2.3 are copies of CF1.1 and CF2.1 designs

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FIGURE 1 Test filters/separators.



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by unknown manufacturers. CC1-CC3 are settling chamber-type devices (often termed "catch cans") from various manufacturers. The separators investigated are summarized in Table 1 (the cyclone could not be disassembled, so the "?" represents uncertainty over internal stricture/media). It is believed that products (4,8) were made by the same manufacturer and products (3,7) were made by a second manufacturer, as each group of two filters shared unique deviations in casting and media type from the original products (1,6), yet product groups (4,8, 3,7) were different from each other.

Figure 1(A) allows comparison of the filter elements from the three of CF1 variants where 1(B) shows the CF2 variants, 1(C) shows the "catch cans," and 1(D) presents the cyclone separator (note that this is an OEM-type device, rather than a common aftermarket offering). The center element CF2.2 appears visually similar in construction to the genuine CF2.1 element on the right; however, it can be observed that it is significantly thinner—obviously containing less filter media. CF2.3 has a wire mesh screen in place of a filter, as did CF1.4.

Figure 2 presents the dismantled photos of catch can separator group. CC3 is a simple settling chamber; however, the inlet and outlet are adjacent. CC2 is a more traditional settling chamber layout, with inlet and outlet on opposite sides of the chamber (achieved via baffles). Stainless steel wool of 80±5 µm is placed in the center of the chamber for additional separation. CC1 contains a U-shaped flow path between the inlet and outlet, with stacks of mesh screens, separated by O-rings on each of the vertical parts of the U. As such it is closest to CF1.4 and CF2.3 in separation principles.

The CF designs are generally filters. It is well established that filtration efficiency is inversely proportional to fiber of the separation media [21]. As such, CF1.1, CF1.2, CF1.3, CF1.5, CF2.1, and CF2.2 all have a nonwoven (felted) fibrous media of approximately 8 µm diameter as the separation media. CF1.3 and CF2.2 only have approximately 3 mm thickness of this filter media, whereas the other systems have ~10 mm in the flow direction. CF1.4 and CF2.3 have a wire mesh screen instead of

TABLE 1 Separators studied.

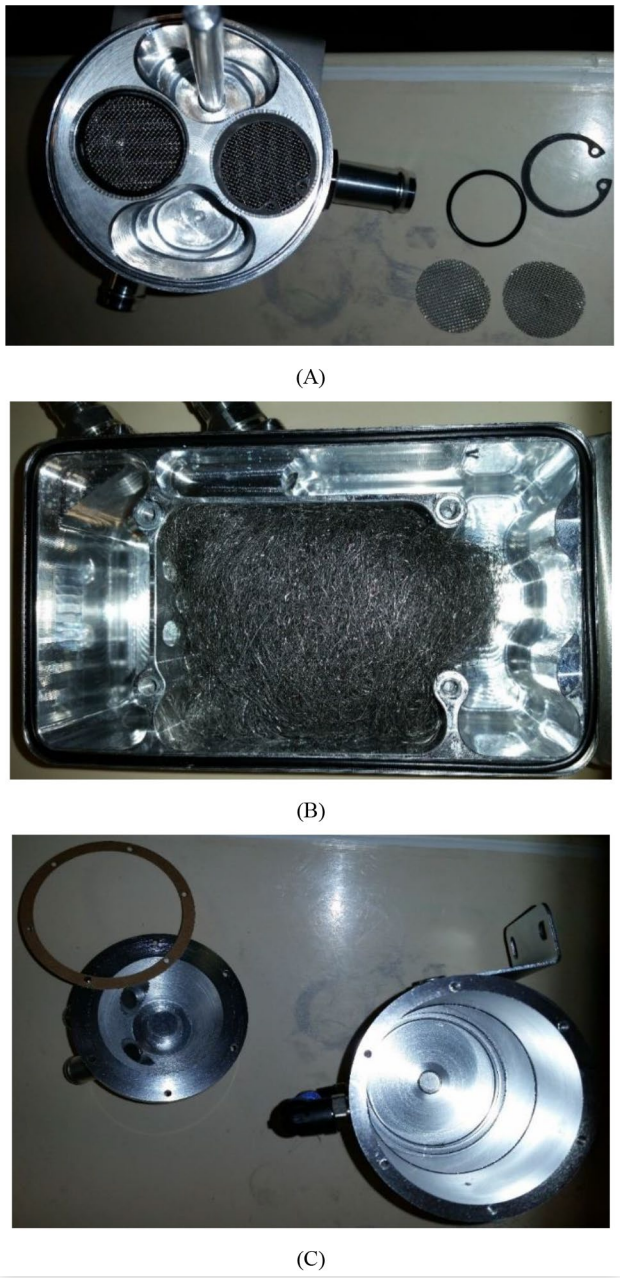
No.	Crankcase filters	Filter type	Branding
1.	CF1.1	Fibrous element	MANN+HUMMEL
2.	CF1.2	Fibrous element	Flashlube
3.	CF1.3	Fibrous element	None shown
4.	CF1.4	Wire mesh	None shown
5.	CF1.5	Fibrous element	MANN+HUMMEL
6.	CF2.1	Fibrous element	MANN+HUMMEL
7.	CF2.2	Fibrous element	None shown
8.	CF2.3	Wire mesh	None shown
9.	CC1	Catch can (mesh screen)	High Performance Diesel (HPD)
10.	CC2	Catch can (wire "wool")	Taipan
11.	CC3	Catch can (empty settling chamber)	Calibre
12.	Cyclone	Cyclone (no element?)	MANN+HUMMEL

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FIGURE 2 Dismantled catch can separators. (A) CC1, (B) CC2, (C) CC3.



(A)

(B)

(C)

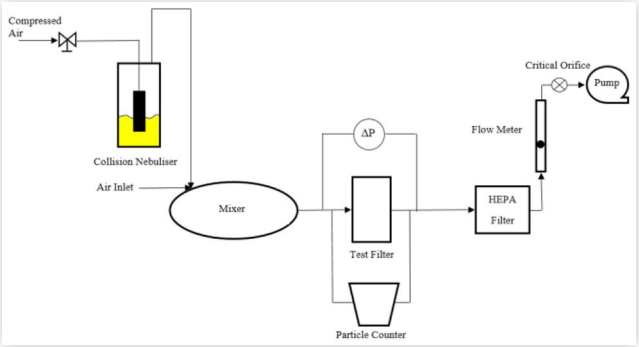
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a filter. They can therefore be considered closer to CC1 in terms of construction, albeit with a significantly larger surface area.

Test Procedure and Apparatus

Figure 3 shows the experimental apparatus, as used in previous studies of mist/crankcase filter performance [13, 14, 20]. No suitable standard currently exists for testing mist filters. The ISO/TC22/SC5 Standard is currently under development for both on-engine and bench testing; however, it has not yet been

FIGURE 3 Test apparatus.



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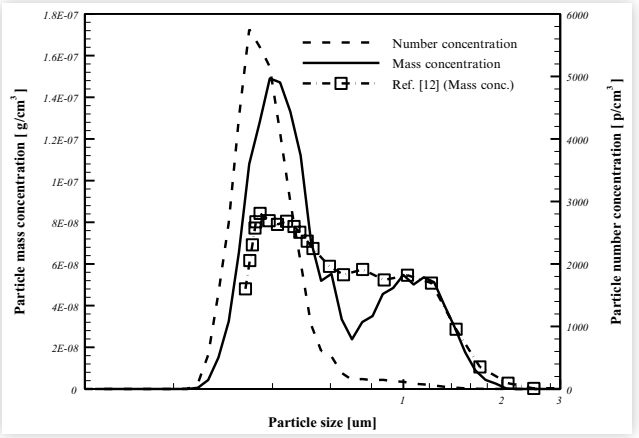
finalized. It is expected that the final bench testing procedure will be in agreement with the established method used in our laboratory (which is equivalent with existing standards for mist filter testing—e.g., air/oil separators for compressed gas cleaners).

Filters were tested at flow rates between 50 and 250 liters per minute (lpm), supplied via a vacuum pump. For measuring "wet" pressure drop, 100 ml of LS W 40 engine oil (Castrol RX Super, Australia) was poured into the separators, and excess allowed to drain for 24 hours. The filter was then supplied with air for 30 minutes to allow excess oil to drain before conduct testing.

Filtration efficiency tests used di-ethyl-hexyl-sebacate (DEHS) aerosol, generated using a Collison-type nebulizer. Figure 4 shows the (stable) aerosol size distribution produced by the system. The test aerosol used by Kissner et al. [12] is also shown, which is equivalent to our test aerosol with respect to size range.

Particle/droplet measurement was conducted using a white-light optical particle spectrometer (PALAS, WELAS PROMO, Karlsruhe, Germany). All tests were repeated a minimum of three times at each flow rate/filter combination. Averaged data are shown; however, error bars are not given in the figures to aid readability. A flow meter (4040, TSI, Shoreview, MN) was used. Pressure drop was measured using a differential pressure transducer (AUJ 8215, Australia).

FIGURE 4 Particle-size distribution before the filter.



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Results and Discussion

In order to compare the different filters and separators, three parameters were studied, dry and wet pressure drop (ΔP), dry collection efficiency (E), and filter quality factor, which are calculated from both (ΔP) and (E).

Pressure Drop Results

Figure 5 shows the comparison of clean pressure drop and wet pressure drop against volumetric flow rate of the CF2 class of filters (6, 7, and 8).

As can be seen, filter CF2.3 had the lowest corresponding clean pressure drop for each flow rate, while filter CF2.1 showed the highest clean pressure drop. At the maximum tested flow rate of 250 lpm, filter CF2.1 was approximately 5 mbar more than the lowest filter in this class CF2.3. The highest pressure difference between clean and pre-saturated filters belongs to CF2.1, while the lowest amount goes to CF2.3. This is because CF2.1 filter retained oil more in the elements. Previous works [13, 14] found that these filters retain approximately 80 g of oil. However, this would correspond to long-term (~1000s of hours) use in most of the cases, so wet pressure drop values may not be representative of the same time point/lifespan. CF2.3 showed a large amount of wall flow (oil detachment) in the outlet indicating the media was poor at resisting re-entrainment. The pressure drop for the CF2.1 filter will be used as a benchmark value for subsequent figures.

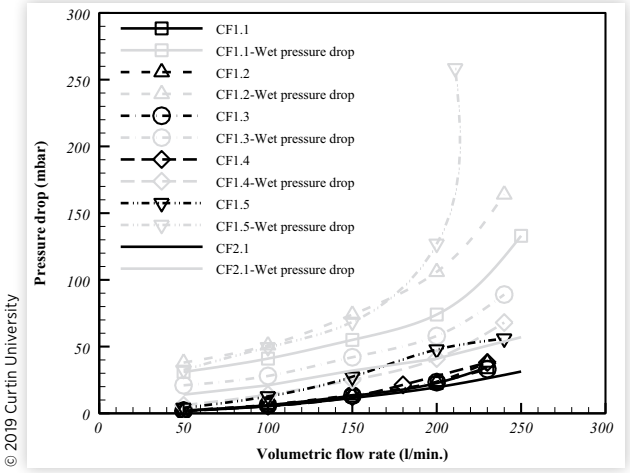
Figure 6 shows the clean and wet pressure drop against volumetric flow rate for the CF1 class of filters (1-5).

In this group it was observed that filter CF1.5 produced the highest clean pressure drop, significantly above all other filters in this class and higher than the benchmark filter CF2.1 from Figure 5. The remaining four (CF1 size) filters (1-4) all show very similar clean pressure drop values, which suggests that the pressure drop in this case is dominated by the geometry of the housing. In the case of wet pressure drop, it is evident from Figure 6 that filter CF1.2 had the highest difference in clean and wet pressure drop among all study cases, and the CF1.4 had the lowest amount.

The pressure drop results for "catch can"-type separators are shown in Figure 7. In this group, the highest clean pressure drop was recorded using separator CC2 and the lowest with separator CC3.

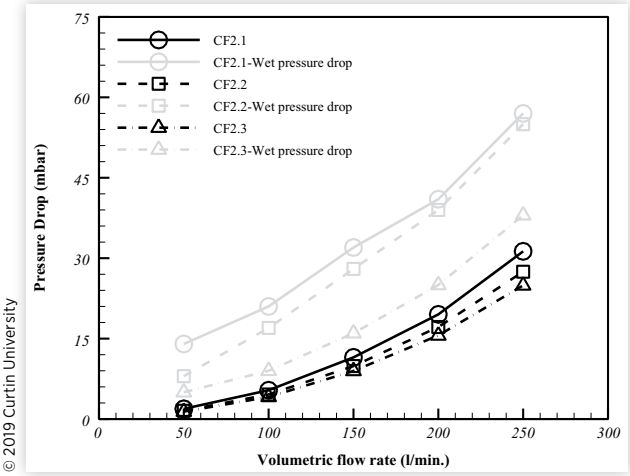
Most surprisingly, however, is that the pressure drop values are significantly higher than the reference filter CF2.1 values, although separator CC3 was reasonably close (it should again be noted that CC3 contains no media and has an adjacent inlet and outlet—see Figure 2C). This high pressure drop however suggests that issues with the design may exist, since settling chambers can typically be expected to offer a lower pressure drop. Wet pressure drop tests were not performed for CC3 as it had no media to retain oil. As shown

FIGURE 6 Pressure drop versus flow rate for CF1 class filters.



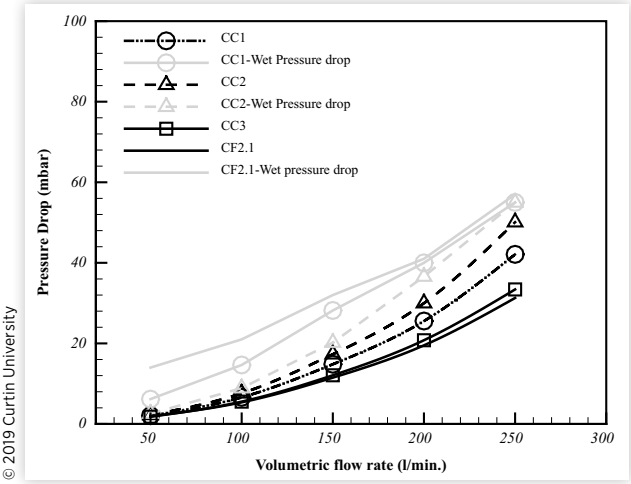
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FIGURE 5 Pressure drop versus flow rate for CF2 class filters.



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FIGURE 7 Pressure drop versus flow rate for CC separator group.

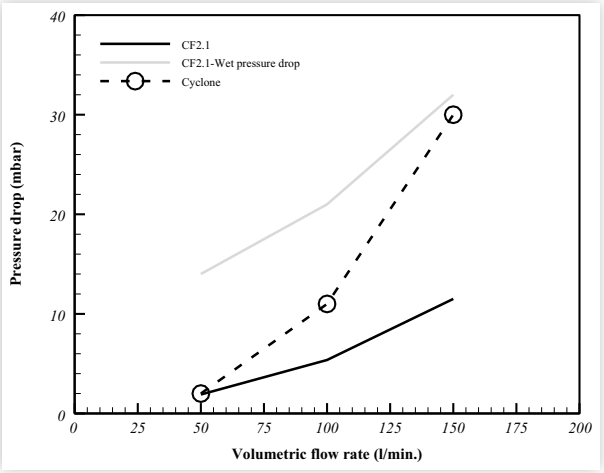


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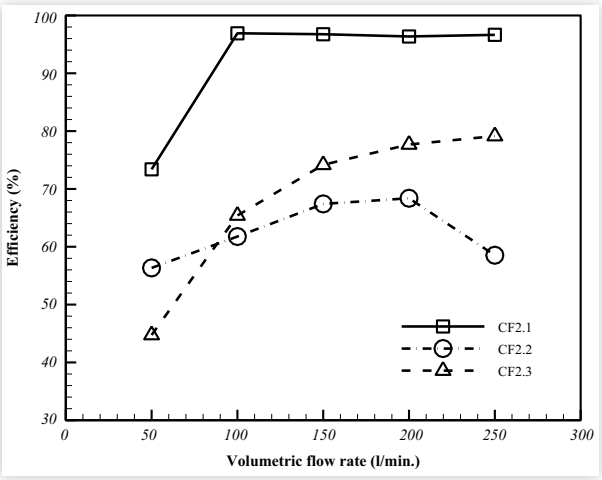
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FIGURE 8 Pressure drop versus flow rate for the cyclone separator.



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FIGURE 9 Efficiency versus flow rate for CF2 filters.



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in Figure 2 (B), the CC2 separator is filled with stainless steel fibrous media with average diameter of 80 ± 5 μm. This media not only produces a high pressure drop; it has a low efficiency due to its large diameter [21]. Figure 2 (A) indicates that CC1 has a stacked mesh arrangement. This mesh produces less pressure drop in comparison with wire wool in the CC2 separator and prevents re-entrainment more effectively.

The pressure drop test results of the cyclone-type separator are given in Figure 8. It can be observed that the clean pressure drop of the cyclone-type separator is higher than reference filter CF2.1 values, similar to the CC3 results. Wet pressure drop tests were not conducted for the cyclone separator as it is believed it had no media to retain oil.

Capture Efficiency Results

Mass-based filter capture efficiency is calculated based on the fraction or percentage of particles/droplet mass which are captured by the filter. A value of 100% means that the entire mass of oil mist was captured by the filter.

Figure 9 shows the comparison of mass-based particle capture efficiency for the CF2 filter class.

It can be seen from the graph that a clear difference exists between devices, with filter CF2.1 clearly superior. For most flow rates, filter CF2.1 operated at 95-98% capture efficiency, whereas filter CF2.3 was consistently below 65% and CF2.2 below 75% for the majority of flow rates examined. A surprising finding, however, was that filter CF2.3 was generally better than filter CF2.2, despite the element in CF2.3 using mesh screens rather than real filter media. As with the pressure drop results, the efficiency results for CF2.1 will be used as a benchmark in further graphs.

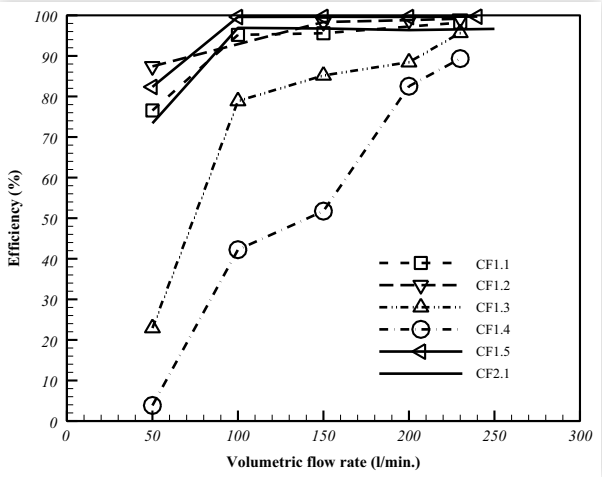
Figure 10 displays the efficiency results for the CF1 class of filters. It can be seen that filters CF1.1 and CF1.2 are the most efficient, comparable to the efficiency of filter CF2.1. Filter CF1.5 is also comparable—in fact recorded the highest efficiency of all filters by a small margin. Filters CF1.3 and CF1.4 showed significantly lower efficiency; however, in this case the filter with a mesh element CF1.4 proved worse than the media element CF1.3.

The third group investigated from an efficiency perspective were the catch can separators (9-11), with the results presented in Figure 11.

As can be seen from this figure, all catch cans demonstrated similar performance, however, at a level significantly lower than the reference filter CF2.1. Efficiency increased as high as 70% at 250 lpm; however, in most applications this flow rate would not be reached. Given the three catch cans converge at 200 lpm and above, it is likely that most deposition in this region occurs through impaction on walls/bends in the geometry.

Figure 12 indicates the cyclone efficiency results. An average of 63% difference between the two, the CF2.1 and the cyclone efficiency, can be observed. As noted by previous studies ([17, 18]), cyclone CCV devices have a low efficiency

FIGURE 10 Efficiency versus flow rate for CF1 filters.

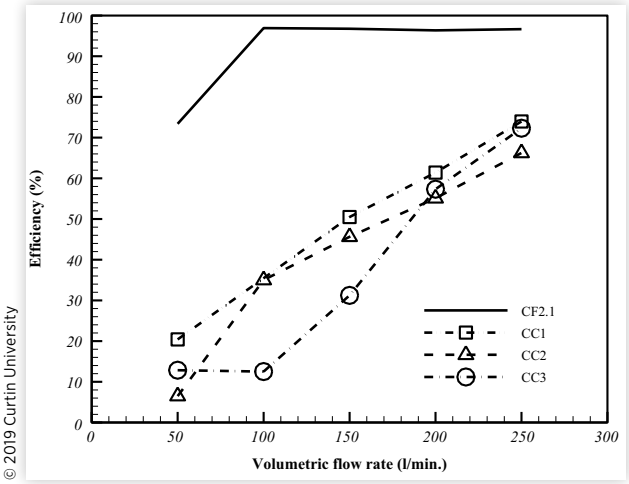


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FIGURE 11 Efficiency versus flow rate for CC separators.



for small particles (d_p < 0.1 mm), as cyclones are optimized for collecting super micron particles (>1 µm).

It should be noted that these tests were performed with new, non-oil-loaded media. Filtration efficiency may also reduce slightly for some particle sizes; however, the overall mass-based filter efficiency would be similar, especially at higher flow rates dominated by inertial separation [21].

Filtration Criterion

The filter quality factor or filtration criterion (γ) is an established method of comparing different filters for the same application at the same flow rate [21]. It is calculated using the formula:

$$\gamma = \frac{-\ln(P_e)}{\Delta P} \qquad \text{Eq. (1)}$$

FIGURE 12 Efficiency versus flow rate for the cyclone separator.

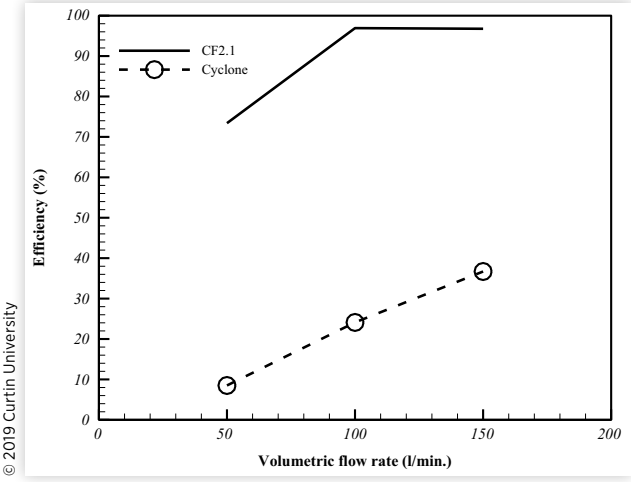
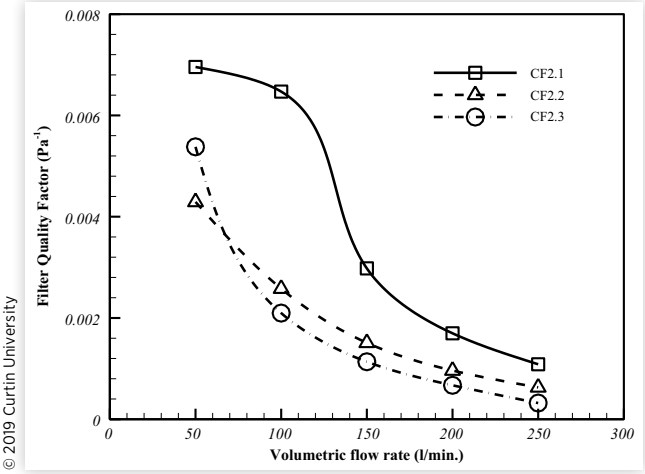


FIGURE 13 Quality factor versus flow rate for CF2 class filters.

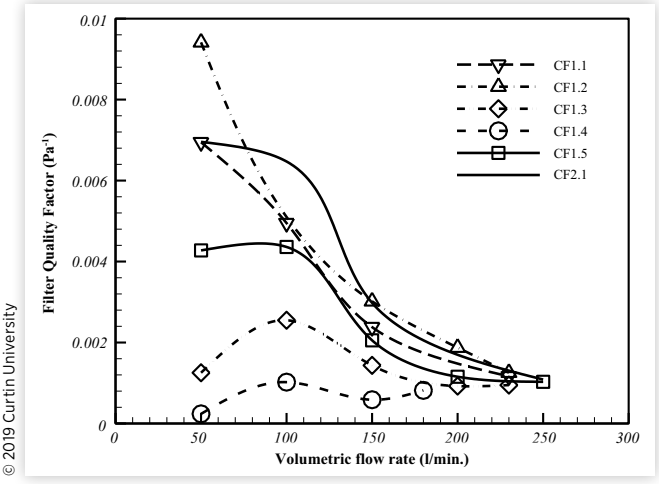


where ΔP is the pressure drop across the filter and Pe is the penetration through the filter (Pe =1 – E, where E is fractional efficiency). Figure 13 shows quality factor calculated versus flow rate for CF2 filter class.

It is evident from Figure 13 that the CF2.1 filter has a higher quality at all flow rates, specifically at lower flow rates. As with the pressure drop and efficiency results, the quality factor results for CF2.1 will be used as a benchmark in further graphs.

Figure 14 depicts the quality factor results for CF1 class. It can be deduced from this figure that by increasing the flow rate, the difference between the quality of filters in this class converges. The major difference in this filter class occurs at flow rates ≤150 lpm. In this class, CF1.2 and CF1.1 indicate the best performance, similar to CF2.1 at most flow rates, while two imitation CF1.3 and CF1.4 filters demonstrate the worst quality at all flow rates ≤250 lpm.

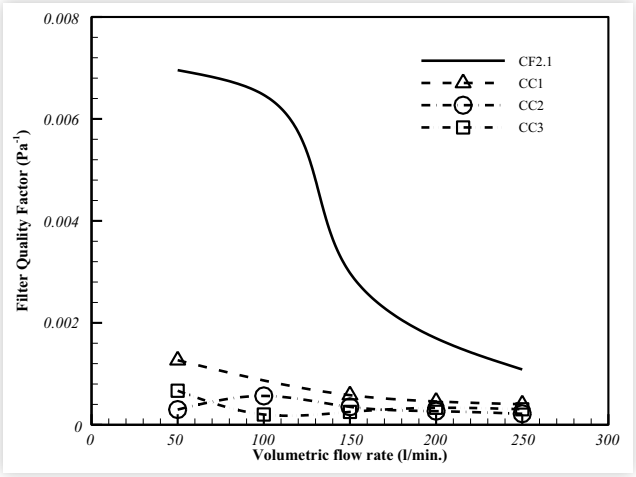
FIGURE 14 Quality factor versus flow rate for CF1 filters.



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FIGURE 15 Quality factor versus flow rate for CC separators.



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The comparison of quality factor for catch can class is presented by Figure 15.

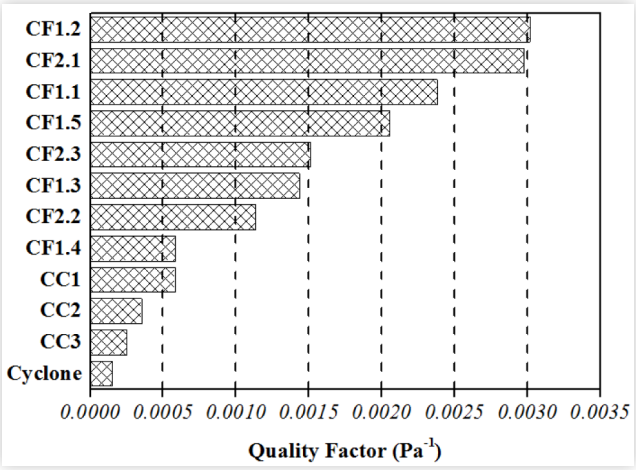
Similar to the previous represented pattern, the quality of the separators decreases by increasing in flow rate, but in this class this slope is marginal. As it is clear from this figure, all these catch can separators have similar quality factor and their main difference occurs at 50 lpm which indicates CC1 with higher quality factor in comparison with other two separators. An interesting point which should be mentioned in this graph is the vast difference between the CF2.1 bench mark filter with the catch can separators. It is clear that the difference at all flow rates is significant.

To provide a comparison of all filters and separators tested, Figure 16 shows quality factor at 150 lpm.

As can be seen from Figure 16, the CF1.2 is clearly the best filter of those tested, closely followed by the CF2.1 and CF1.1. The worst separators (CC3 and cyclone) were 12 times and 20 times worse than the best filter (CF1.2) based on quality factor, respectively.

It should be noted that these tests were conducted based on dry pressure drop data. This was considered most representative as the different devices would be expected to have vastly different operational lifespans to reach saturation (maximum oil holding).

FIGURE 16 Filter quality factor. Higher values indicate a better filter.



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Conclusion

This work examined 12 different CCV separators including 8 filters, 3 catch cans, and 1 cyclone. Some overlap in design was found, especially as some "filters" only contained mesh screens, as did one of the catch cans, while one of the catch cans included a (coarse) wire wool, which begins to approximate the nonwoven felts in the true filters. Pressure drop, capture efficiency, and quality factor perspective were examined for all devices. It was found that CF2.1 and CF1.2 had the lowest dry pressure drop in their category, and they had higher capture efficiency. In consequence, all these two filters showed the highest quality factor among all tested filters. On the other hand, all catch can-type separators and the cyclone imposed high resistance to air flow in the system, coupled with low capture efficiency, which resulted in a poor quality factor for both types of devices.

Contact Information

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