## Results

This study was conducted from May 2012 through February 2015 during construction activities within a building. The study included 83 deployed PHEAF units from 5 known manufacturer models. Three devices were not labeled with the manufacturer and were categorized as unknown. The 6 manufacturers are denoted A, B, D, E, F, H in this study. Six units were missing nameplates, but their design was typical of PHEAF devices used in the environmental remediation industry. The study spanned 9 test rounds resulting in 324 paired measurements taken at the intake and exhaust locations of each PHEAF device. Manufacturer model E made up 87% (281 out of 324) of the recorded tests. Many of the PHEAF units were measured multiple times across different test rounds. The intervals between test rounds and the number of units tested in each round varied depending on ongoing construction activities.

A total of 141 tests were made by **hotwire anemometer technique** during test rounds 1 to 3. Only PHEAF devices from manufacturer models E, F, and H were available during these rounds. Subsequently, 183volumetric tests were taken by the **balometer capture hood technique** in rounds 4 to 9. Table 1 shows the mean airflow volumes measured by each technique at intake and exhaust grouped by manufacturer model. We find that the average airflow volume was predominantly measured to be less than the manufacturers claimed capacity. For example, a PHEAF model having a claimed airflow of 1975 cfm had a measured average airflow (i.e., (intake + exhaust)/2) of 1127cfm by hotwire anemometer and 1250 cfm by balometer, which were respectively 43% and 37% lower than the advertised capacity. Generally, both techniques recorded device capacities substantially lower than the claimed capacity, with the balometer having higher readings than the hotwire anemometer on average.

Table 1: Summary of airflow volume for PHEAF manufacturer models having at least 6 measurements taken by hotwire anemometer or balometer capture hood

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PHEAF manufacturer model | Manufacturer claimed airflow (cfm) | N | | Mean intake, cfm (SD) | | Mean exhaust, cfm (SD) | | Percent reduction from manufacturers claimed airflow+ | |
|  |  | **Anemometer** | **Balometer** | **Anemometer** | **Balometer** | **Anemometer** | **Balometer** | **Anemometer** | **Balometer** |
| D | 1,900 | 0 | 7 | \*\* | 929.1  (201.4) | \*\* | 1033.6  (253.9) | \*\* | 48.3  (11.9) |
| E | 1,975 | 126 | 155 | 1025.6 (402.4) | 1190.6 (398.0) | 1229.7 (562.3) | 1306.2 (427.1) | 42.9  (25.2) | 36.8  (21.1) |
| F | 1,000 | 6 | 0 | 977.5  (257.3) | \* | 1129.3  (217.6) | \* | -5.3  (24.1) | \* |
| H | 2,100 | 7 | 14 | 1025.4 (211.3) | 1304.8 (187,1) | 2284.9 (595.6) | 1510.0 (222.4) | 21.2  (37.2) | 33.0  (10.8) |

+ The percent reduction is computed using the average of the intake and exhaust measurements.

\* Surface area of PHEAF unit was not of sufficient size for balometer capture hood measurement to seal again the unit’s cabinet

\*\* PHEAF units were not available during the period hotwire anemometer data collected

\*\*\* Measurements taken by hotwire anemometer and balometer capture hood were collected at different periods of the study

A deeper look at the data collected from devices from manufacturer model E showed that the hotwire anemometer was not only giving smaller airflow measurements on average, but was also more prone to give extreme measurements than the balometer (Figure 2). While the median measurements from the hotwire anemometer were quite a bit lower than the claimed capacity of 1,975 cfm, 3 intake measurements and 15 exhaust measurements exceeded 2100 cfm, the highest claimed capacity of any manufacturer model. We also note here that intake measurements are generally lower than exhaust measurements on average. For the remainder of this section, we limit our analyses to data from manufacturer model E.

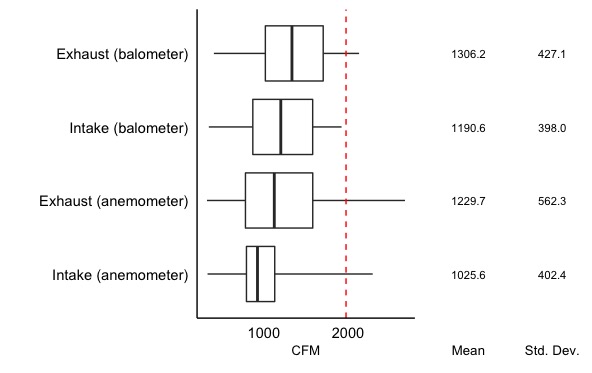


Figure 2: Distribution of hotwire anemometer and balometer readings in this study, grouped by location, for   
PHEAF Model E. The red line denotes the manufacturer's advertised capacity of 1,975 cfm

We note here that we cannot directly assess accuracy of our measurements since we did not use any gold standard method to measure the airflow through each unit at each test. We can assess consistency of measurements by location and technique through the estimated variability of the measurements. We can see (Figure 2) that the exhaust anemometer readings are substantially more variable than the other three readings. These standard deviation estimates do not, however, take into account the fact that repeated measurements have been taken on the same machines over different test rounds. We account for the repeated measures by fitting random intercept models with volumetric readings nested within PHEAF units; the within-unit standard deviation (SD) represents an estimate of the measurement error for the particular technique-location combination (Table 2). We observe that the exhaust hotwire anemometer readings are significantly inferior (i.e., has a higher variability) to the other three measurement techniques, which are roughly equivalent.

We note that the intake hotwire anemometer volume measurement is quantified as an average of 9 sector-based measurements. Table 3 summarizes the airflow velocities measured at each sector; the volumetric measurements are derived from these by multiplying by the face area. These measurements are highly correlated (minimum pairwise correlation of 0.95) resulting in the average across the 9 sectors not having a lower variability than an individual sector measurement, but involving 9 times the work. The nine measurements are also not significantly different from each other; a one-way repeated measures ANOVA F-test (*F8,1075*) gave a p-value of 0.25. The balometer capture hood measurement involves a single measurement, and as evidenced by the within-unit SD estimates in Table 2, perform similarly regardless of the location of the measurement (intake vs exhaust). The center sector velocity measurements have the lowest variability of all the sectors (Table 3), which is reflected in the low within-unit SD of the volumetric measurement in Table 2; it also has the lowest average measurement which makes it most discrepant from the advertised airflow of the machine.

Table 2: Estimates of measurement error for different volume measurement techniques (manufacturer model E)

|  |  |  |
| --- | --- | --- |
| **Measurement Technique** | **Within unit SD** | **95% Confidence Interval** |
| Intake volume hotwire anemometer | 252.1 | 241.7-295.9 |
| Exhaust volume hotwire anemometer | 409.8 | 349.2-480.9 |
| Center sector volume hotwire anemometer | 228.4 | 194.4-268.2 |
| Intake volume balometer | 272.4 | 238.6-310.9 |
| Exhaust volume balometer | 303.1 | 265.4-346.1 |

Table 3. Face velocity measured at 9 filter sectors on PHEAF manufacturer model E   
[mean (CV)]

|  |  |  |
| --- | --- | --- |
| **Sector 1**  295.0  (43.9) | **Sector 2**  297.2  (41.3) | **Sector 3**  296.8  (41.6) |
| **Sector 4**  287.2  (42.9) | **Sector 5**  279.2  (37.8) | **Sector 6**  287.3  (40.6) |
| **Sector 7**  290.2  (42.1) | **Sector 8**  283.2  (38.6) | **Sector 9**  285.5  (40.3) |

**Relation between intake and exhaust measurements**

One would expect that for machines in good working order, the airflow measurements at the intake and exhaust would be similar. Figures 3 and 4 show the intake and exhaust airflow measurements at each test for PHEAF Model E units for the hotwire anemometer and balometer respectively. We fit simple linear regression lines to the data. The hotwire anemometer shows increased outliers at lower intake airflow volumes. The slope of the line is 0.84 (95% CI 0.64-1.04) showing a strong positive relationship, but the regression line only explains 36% of the variability of the exhaust measurements.

Figure 3: Simple linear regression model of intake volume and exhaust volume as measured by hotwire anemometer for PHEAF Model E

The balometer shows a tight correspondence between intake and exhaust measurements. The slope of the regression line is 1.05 (95% CI 1.0-1.09), and the regression explains 96% of the variability of the exhaust measurements.

Figure 4: Simple linear regression model of intake volume and exhaust volume as measured by balometer capture hood for PHEAF Model E

This analysis is indicative of the fact that the balometer measurements are far less dependent on the location of measurement that the hotwire anemometer, pointing to their consistency in making airflow measurements compared to the anemometer.

**Significance of Volume Measurement**

The relationship between measured airflow and the calculated photometer setting is illustrated in Table 4 and Table 5. The airflow reference in the tables reflects the mean values reported in this study for intake volume by the hotwire anemometer (1,025 cfm) and exhaust volume by balometer capture hood (1,308 cfm). For this scenario, the balometer capture hood is identified as the actual air volume value. Accordingly, an observed 0.03% particle penetration would classify the filter efficiency as 99.97%. However, if the actual airflow volume through the PHEAF was 1,308 cfm the corrected filter efficiency would be 99.96%. While the difference in % capture efficiency between the measured and actual values is less than 1%, the measured lower airflow would suggest the filter is more efficient than reality.

Table 4. Effect of volume measurement on percent capture efficiency when particle penetration is measured at 0.03%

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Measured** | **Actual** |
| Airflow | 1,025 cfm (hotwire anemometer) | 1,308 cfm (balometer capture hood) |
| Photometer 100% setting | 26 mg/m3 (calculated) | 21 mg/m3 (actual) |
| Photometer reading | 0.03% (observed) | 0.037% (corrected) |
| % Capture efficiency | 100%-0.03%=99.97% | 100%-0.037%=99.96% |

Table 5 shows a similar scenario but emphasizes the magnitude of the airflow effect as the observed percent particle penetration through the HEPA filter increases. In this example, a 10% particle penetration results in a difference of 8.4% between the measured capture efficiency and actual % capture efficiency.

Table 5. Effect of volume measurement on percent capture efficiency when particle penetration is measured at 10%

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Measured** | **Actual** |
| Airflow | 1,025 cfm (hotwire anemometer) | 1,308 cfm (balometer capture hood) |
| Photometer 100% setting | 26 mg/m3 (calculated) | 21 mg/m3 (actual) |
| Photometer reading | 10.0% (observed) | 12.38% (corrected) |
| % Capture efficiency | 100%-10.0%=90.0% | 100%-12.38%=87.62% |