Assured containment at low airflow has long eluded the users of ventilated enclosures including chemical fume hoods used throughout industry. It is proposed that containment will be enhanced in a hood that has a particular interior shape that causes a natural vortex to occur. The sustained vortex improves the containment of contaminants within the enclosure at low airflow. This hypothesis was tested using the ASHRAE 110 tracer gas test. A known volume of tracer gas was emitted in the hood. A MIRAN SaphIRE infrared spectrometer was used to measure the concentration of tracer gas that escapes the enclosure. The design of the experiment included a written operating procedure, data collection plan, and statistical analysis of the data. A chemical fume hood of traditional design was tested. The hood interior was then reconstructed to enhance the development of a vortex inside the enclosure. The hood was retested using the same method to compare the performance of the traditional interior shape with the enhanced vortex shape. In every aspect, the vortex hood showed significant improvement over the traditional hood design. Use of the Hood Index characterizing the dilution of gas in an air stream as a logarithmic function indicates a causal relationship between containment and volumetric airflow through an enclosure. Use of the vortex effect for ventilated enclosures can provide better protection for the user and lower operating cost for the owner.

To evaluate the dynamics of air motion inside a partially enclosed space, it is necessary to challenge a long-held belief among ventilation specialists that face velocity is an indicator of hood performance. An added concept of this investigation is that volumetric airflow, rather than face velocity, is a true indicator of hood performance. The prevailing laboratory ventilation standard cautions that face velocity alone is an inadequate indicator of hood performance. Current guidelines do not provide an accurate means to determine the volumetric airflow required for laboratory chemical hoods. Traditionally, volumetric airflow is calculated by multiplying a face velocity over an open face area. This is ambiguous because face velocity is a range of values (0.30–0.50 m/s, 60–100 fpm) and open face area is a variable depending on sash position.

Air in motion must have volumetric flow in liters per second (l/sec) (cubic feet per minute (cfm)). The air mass also has velocity in meters per second (m/sec) (feet per minute (ft/min)) as it passes through any plane of limited area. Volumetric flow and face velocity exist simultaneously as separate aspects of airflow. Intuition suggests that the volumetric flow of air passing through an enclosure is the critical function for achieving containment. Conversely, the velocity of air passing through a single plane is an incidental function of airflow that has little relation to containment.

The internal volume of a laboratory chemical hood is constant. The movable hood sash causes variable open face areas. It is reasoned that a constant volumetric flow of air should be maintained.
be determined independently from face velocity. Then, face velocity is a variable result of volumetric airflow and changing sash position. The volumetric flow of air through an enclosure and the velocity of the air at an open face are distinctly different qualities and must not be thought of as the same.

**METHODS**

A chemical hood of traditional design was selected. Data that characterize hood containment in the traditional hood were measured and recorded. The hood was then modified with a different interior shape. The same measurements were repeated and recorded. The results of the traditional hood were compared to the results of the vortex hood.

The laboratory chemical hood selected for testing had a dedicated fan, a variable frequency drive (VFD), and a Magnehelic gauge reading static pressure in the exhaust duct. The hood was of old-style bench-top construction. It was 8 ft long with three vertical rising sashes and an airfoil.

The experiment apparatus was calibrated to establish fixed relationships between volumetric airflow (l/sec, cfm), adjustable speed of the variable frequency drive in revolutions per minute (rpm), and the static pressure in the exhaust duct in inches of water. Traverse(3) velocity readings were taken in the main exhaust duct (45.72 cm, 18″ wide × 20.32 cm, 8″ deep) using a Short Ridge Instruments Inc. (Scottsdale, Az.), AIRDATA Multimeter ADM 870. This was done iteratively so that the air velocity times the duct area matched the volumetric airflows intended for use in the experiment. The results are given in Table I. The intended volumetric airflow was achieved by setting the corresponding speed on the VFD and verified by the Magnehelic gauge reading.

The interior laboratory hood profile used in the experiment is shown in Figure 1. The baffle was of a traditional type. There was an exhaust slot at the top and bottom of the hood interior.

Industry recognizes the American Society of Heating, Refrigeration and Air-conditioning Engineers, ASHRAE 110 Tracer Gas Test as the best-known, quantifiable method of measuring fume hood containment. This test involves the release of a known amount of tracer gas in the hood or enclosure. An analytical instrument is used to sense the concentration of tracer gas that escapes from the hood.

Sulfurhexafluoride (SF₆) is used as the tracer gas. It is provided in Department of Transportation (DOT) gas cylinders. A regulator allows the SF₆ to be issued at 2 kg/ sq. cm (30 lb/sq. in). The SF₆ cylinder and regulator are connected to the gas diffuser by a flexible metal hose.

The gas diffuser is prescribed in detail by the ASHRAE 110 Tracer Gas Test document. The diffuser is designed to inject 4 l/min of SF₆ inside the hood with 2 kg/sq cm (30 psi) of inlet gas pressure. The diffuser was placed 15 cm (6′) from the face of the hood opening on the work surface during the experiment.

The Tracer Gas Test requires a manikin. The manikin fixes the position of the instrument probe at 1350 mm (54 in) above the floor and 75 mm (3 in) away from the plane of the hood opening. The manikin also represents the obstruction to airflow of a researcher so that the air must flow around the manikin before entering the hood. The manikin was fixed on a base with casters on the bottom. A pole attached to the base was used to move the manikin in front of the hood.

A MIRAN Series 205B SaphIRe Portable Ambient Air Analyzer (Thermo Fisher Scientific Inc., Franklin, Mass.) with a detection limit of 0.01 ppm for SF₆ is used to measure tracer gas that escapes from the hood. It is a highly sensitive analog instrument specifically calibrated to read SF₆. The instrument is set so that the digital display indicates SF₆ in parts per billion (ppb). A flexible hose connects the infrared spectrometer to the probe. The manikin is made to receive the probe in a position that approximates the breathing zone of a researcher.

The verification test was conducted by placing the end of the MIRAN instrument probe directly on top of the diffuser inside the hood. Each verification test lasted 3 min in which 10 to 12 spectrometer readings were taken. This test was conducted at the beginning of each session in which data were recorded.
The experiment included testing at 3 airflows: 240, 380, or 570 l/sec (500, 800, or 1200 cfm). Three diffuser locations inside the hood—right, center, or left—were used. Two conditions were used in the experiment. The manikin, when stationary, was in a static condition. When moved back and forth in front of the hood, the manikin created a dynamic condition. Three airflows times three diffuser locations times two conditions (static, dynamic) require 18 tests to characterize all combinations of the variables.

A table of random numbers was generated to randomize the experimental trials so that volumetric flow, diffuser location, or movement in front of the hood was changed between each test. The hood was tested measuring tracer gas outside the hood with the instrument probe at the face of the manikin. Each test lasted for 3 min during which 10–12 readings were recorded from the instrument display. The test result is the average of the instrument readings. A run of 18 tests was repeated 3 times. Fifty-four tests consisting of ~600 readings were conducted to characterize the performance of the traditional laboratory hood.

The interior of the hood was redesigned with the intent that the air flowing through the enclosure would form a stable vortex. The Fibonacci sequence (5) is used as the mathematical model for the vortex enclosure design. Important features of the design are shape and proportion. The proportion is derived from the Fibonacci sequence in which each number in the series is the sum of the two previous numbers: 1, 2, 3, 5, 8, 13, 21, 34, 55, . . .

As numbers in the series become larger and when any number in the series is divided by the previous number the result converges on an infinitely repeating decimal, 1.618 . . . . This is indicated by Φ. The Fibonacci sequence evolves a unique geometry. When the base isunitary, or 1, and the height is Φ = 1.618 . . . the result is a specific rectangle. If a perfect square is removed from the rectangle, the result is another, smaller rectangle of the same proportion. This continues infinitely. When the diagonal corners of the squares are joined by a smooth curve the result is a specific spiral within the rectangle. Figure 3 illustrates the rectangle and spiral geometry derived from the Fibonacci sequence.
All tests were conducted with the sash fully open so that dilution ratios (Co/Ci) such that gas emitted inside a chemical enclosure are based on the hood working depth “D” which is the distance from the sash face to the rear lining of the enclosure. The interior height “H” from the work surface to the top of the vault is 1.6 times the working depth, or, H = 1.6(D). The single exhaust slot is a height “S” above the work surface. This height “S” is equal to the working depth of the hood, or S = D. The height “O” of the hood open face is less than or equal to the working depth or O ≤ D.

Referring to Figure 4, exhaust air enters the hood or enclosure through the open face 2. Initially, most of the air is exhausted through the single slot 5 in the upper rear of the hood. Some of the exhaust air bypasses the slot and moves along the smooth surface of the vaulted baffling 1, 3, 4 at the top of the enclosure. As the air moves around the top vaulted section of the vortex enclosure, it begins to tumble and roll. The air rolling down the front of the vault meets more exhaust air entering the open face of the hood. The induction of air into the hood results in a stable vortex that forms in the upper middle of the enclosure. Eventually, all of the air is exhausted through the single slot 5.

The traditional baffling was removed from the laboratory hood used in the experiment. New baffling was installed per Figure 4a. Fifty-four tests were repeated to characterize the vortex hood. A total 108 tests were conducted using ~1200 spectrometer readings. The objective of the testing was to distinguish between two different internal enclosure shapes. All tests were conducted with the sash fully open so that the open face area is not a variable that would impact test results.

### RESULTS

The results of the verification tests are uniform over the 7 days the testing was conducted. On the 3 days in which the traditional hood was tested the mean of the verification tests is C_i = 220856 ppb. On the 4 days during which the vortex hood was tested, the mean of the verification test is C_i = 222600 ppb. The mean of all the verification tests is C_i = 221853 ppb.

Across the full range of data, the average of the tracer gas measured outside the traditional laboratory hood was 7686 ppb. The average of the tracer gas measured for the vortex hood was 3582 ppb. The vortex hood reduces the breach of containment by half compared to the traditional hood. The one-way ANOVA tests confirm that, in every aspect measured, the vortex hood demonstrated improved containment over the traditional hood. A summary of the data is tabulated in Table II where C_o is the mean concentration of tracer gas measured outside the hood in ppb distributed over the three different airflows. The same data, in Figure 5, are shown as a bar chart.

Grouping the data using the Tukey Method found for both conditions a statistically significant difference in the data as airflow increased from 240 l/sec (500 cfm) to 380 l/sec (800 cfm). However, there is no statistically significant difference in the data as airflow increased from 380 l/sec (800 cfm) to 570 l/sec (1200 cfm). Therefore, the data neither confirm nor refute a causal relationship between volumetric airflow and containment.

In 1979 it was proposed that air flowing through a chemical hood represents a dilution process characterized by a logarithmic function. A hood index (HI) was established as a guide for researchers to determine the amount of a harmful substance that may be used inside a hood for the sake of experimental safety. The hood index was defined as:

\[
HI = -\log(C_o / C_i)
\]  

Where

- C_o = concentration of contaminants outside the hood
- C_i = highest concentration of contaminants inside the hood
- Containment within an enclosure is characterized by a dilution ratio (C_o/C_i) such that gas emitted inside a chemical hood is reduced from high to low concentrations. The data

| Airflow L/s (cfm) | Traditional Hood C_o (ppb) (Std. Dev.) | Vortex Hood C_o (ppb) (Std. Dev.) |
|------------------|-----------------------------------------|-----------------------------------|
| 240 (500)        | 14045 (11396)                           | 8917 (8064)                       |
| 380 (800)        | 4610 (6299)                             | 1460 (2606)                       |
| 570 (1200)       | 4624 (6708)                             | 316 (759)                         |
(Figure 5) for the vortex hood indicate a pattern of dec- 
lination such that the concentration of tracer gas measured 
outside the hood decreases as the volumetric flow of air 
increases.

The hood index was calculated using the mean values 
(Table II) of $C_o$ corresponding to the three airflows for both 
the traditional and the vortex hood configurations. The values 
for $C_i$ are the averages of the verification tests where the 
instrument probe was placed on top of the gas diffuser. The 
results are tabulated in Table III. The same results are shown 
as a line chart in Figure 6.

The three hood index values calculated for the vortex en-
closure fall on a straight line. Given the highly variable ex-
perimental data, fitting three points so closely to the same 
straight line was unexpected. The linearity of the three hood 
index values for the vortex hood indicates a functional rela-
tionship between the hood index and the volumetric flow of air 
through the hood. Using the formula for a straight line results
in the following:

\[ HI = V_c(Q) + b \]  \hspace{1cm} (2) 

Where

\( V_c = \) the slope of the straight line that becomes the vortex constant
\( Q = \) the volumetric flow of air in l/sec (cfm)
\( B = \) the value of the hood index when \( Q \), the airflow, is zero

Using the three data points for the vortex hood from Table III and averaging, solutions for the constants are: \( V_c = 0.00453 \) when using metric units, and \( V_c = 0.00213 \) using English units. The y-intercept, \( b \), is 0.357 for both measurement systems.

Setting the two definitions of hood index, Eqs. (1) and (2) as equal, the result is:

\[ -\log(C_o/C_i) = V_c(Q) + b \]  \hspace{1cm} (3)
TABLE III. Hood Index Analysis

| Airflow L/s (cfm) | HI - Traditional Hood | HI - Vortex Hood |
|------------------|----------------------|------------------|
| 240 (500)        | 1.197                | 1.397            |
| 380 (800)        | 1.680                | 2.183            |
| 570 (1200)       | 1.679                | 2.848            |
| C_i - Concentration Inside | 220856              | 222600           |
| The Hood (ppb)   |                      |                  |

Rearranging Eq. 3 to solve for volumetric airflow is;

\[ Q = \frac{1}{V_c} \left( -\log(C_o/C_i) - b \right) \]  \( (4) \)

The analysis provides a means to predict a value for volumetric airflow based on a dilution ratio. The value for \( C_o \) is the generally agreed upon standard\(^1\,\,3,4\) for hood containment of 0.1 parts per million (ppm) or \( C_o = 100 \) (ppb). \( C_i \) is 220,000 ppb, the approximate average of all the verification tests. Solving for the volumetric mass flow of air using Eq. 4, the result is:

\[ Q = 696 \text{ l/sec}(1402 \text{ cfm}) \]

Since 316 ppb of tracer gas was measured at 570 l/sec (1200 cfm) on a curve that asymptotically approaches zero as airflow increases, then, achieving dilution to 100 ppb of tracer gas at the predicted value of 696 l/sec (1402 cfm) is consistent with the data collected for the vortex enclosure.

The argument is: if containment is understood to be a dilution process characterized by a dilution ratio, and if the volumetric flow of air can be predicted based on the experimental data, then, for the vortex shape, there is a causal relationship between containment and the volumetric flow of air through an enclosure.

DISCUSSION

Vortex ventilation can be useful in determining the airflow required for different toxicity levels. Threshold limit values\(^5\) (TLV\(^6\)s) of chemical substances are expressed in ppm. This is the same measurement used for the concentration of tracer gas used in hood containment studies. Using the dilution ratio \( (C_o/C_i) \) the appropriate volume of air may be determined using Eqs. (3) and (4). It is not known whether the vortex constant \( V_c \) is representative of all ventilated enclosures having the enhanced vortex shape. Further testing of different vortex hoods will be necessary to make this determination.

Industrial ventilation\(^4\) indicates that increasing face velocity does not necessarily improve containment. The results of the vortex enclosure experiment (Figure 5) indicate concentration \( (C_o) \) outside the hood approaches zero asymptotically as airflow increases. However, like face velocity, there is a point beyond which increased airflow causes less dilution and therefore less improvement of containment.

To operate the laboratory chemical hood efficiently, it is necessary to find a point that will achieve both high containment and low airflow. A volumetric airflow of 425 l/sec (900 cfm) is selected as an intuitive estimate. Using Eq. (2), 425 l/sec (900 cfm) resolves a hood index \( HI = 2.28 \). Using Eq. (1) iteratively, the dilution ratio \( (C_o/C_i) \) becomes \( 1/190 \). When this dilution ratio is expressed as a percent, 99.5% of the tracer gas emitted in the hood would dissolve in the air stream inside the hood with the sash fully open.

A test was devised to confirm that the vortex hood with a constant volume of 425 l/sec (900 cfm) meets the currently accepted performance criteria. This test added sash movement and positioning. The face velocity was 0.6 m/sec (129 ft/min) with one sash open. With two sashes open, the face velocity was 0.3 m/sec (64 ft/min). With all three sashes half open, the face velocity was 0.44 m/sec (86 ft/min). Nine tests comprised of 76 spectrometer readings were conducted. The average of all the test points was 36 ppb (0.036 ppm). This is well within the 100 ppb (0.1 ppm) limit generally accepted by industry as a performance standard.\(^2,4\)

The fume hood with the enhanced vortex shape had an internal volume of 2124 l (75 cubic ft). Four hundred and twenty-five l/sec (900 cfm) divided by 2124 ls (75 cubic ft) results in 0.2 air changes/sec, or, 12 air changes/min. It is likely that 12 air changes/min is a sufficient volume of air for the vortex enhanced chemical hood to achieve effective containment when in use. Independent testing is needed to validate this assumption.

Figure 7 shows a ventilated enclosure made to demonstrate the vortex effect. A fog machine is used to diffuse smoke in the lower front of the enclosure. A fan is used to remove the smoke from the top of the chamber. The spiral path of air moving inside the enclosure is visible especially when viewed from the side of the chamber in profile.

CONCLUSION

The study is limited because some aspects of airflow were not considered or resolved by the experiment. The conventional understanding\(^4\) of air flowing through a partially enclosed space is that conditions outside and inside the hood challenge hood performance. Some of those conditions are the way makeup air enters the room, motion in front of the hood, and, the way a laboratory hood is loaded with apparatus.

It is probable that the vortex hood is more resilient to these challenges than the traditional hood. Half of the tests were conducted with no movement, while half of the tests were conducted with the manikin being moved back and forth in front of the hood. The traditional hood showed improved containment with no movement, while the vortex hood showed improved performance with movement in front of the hood. The differences in the data, however, were not significant enough to draw a conclusion about performance with respect to movement in front of the hood.

It is also likely that the vortex hood is more resilient to loading because the vortex occurs above the apparatus placed in the hood and the single exhaust slot is raised above the work...
This is not confirmed because testing was done with the hood empty and loading was not a variable in the experiment.

Safety professionals require the means to evaluate, establish, and audit conditions wherever ventilation is used to protect people from harmful substances. Calculating exhaust loads in terms of air changes over time (per second, or per minute), provides discrete results for all ventilated enclosures including chemical hoods. Using air changes per minute, calculated airflow has the same result for a laboratory chemical hood as a ventilated enclosure, with sash or no sash and regardless of sash type or open face area.

Tracer gas testing has been used for decades to evaluate laboratory hood performance. A causal relation between containment and face velocity, independent of volumetric airflow, has not yet been demonstrated. This experiment demonstrates significant improvement in hood performance, and, a causal relation between containment and volumetric airflow, independent of face velocity. Continued study of the vortex effect provides an avenue to advance the art of ventilation.

ACKNOWLEDGMENTS

Sincere thanks and appreciation is extended to my colleagues at E.I. duPont de Nemours for help, guidance, and support. They are Barbara Dawson, Gee Joseph, Aaron Chen, John Rydzewski (retired), William Moye, Joseph Hockman, Frank Olszewski (retired), Joseph Lala, John Fitzpatrick, Michael Glasspool, and Vincent Games (associate). All resources and funding for this effort were made available by the DuPont Company. A patent application has been submitted for the general hood design shown in Figure 3.

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