# An Educational Experiment on Modelling Fume Hood Face Velocity as a Function of Sash Opening Area

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## ABSTRACT

This study developed an experiment to investigate the relationship between fume hood sash opening area and air velocity. This experiment was developed using a constant air volume fume hood (CAV). The experiment was designed as a practical application of the continuity equation, Q=AV, for the Industrial Hygiene students. The developed experiment is presented as a proposed practical teaching framework for Industrial Hygiene engineering control modules, allowing students to bridge theoretical fluid mechanics with real-world equipment behaviour. This equation states that the volumetric flow rate (Q) is equal to the product of area (A) and velocity (V). The dimension of the fume hood used in this study is 460 mm (maximum height) and 1422 mm wide. The opening was tested at 100%, 75%, 50%, and 25% of the maximum height. The sash was divided into a grid, with the maximum size not exceeding 150 mm × 150 mm. The number of horizontal and vertical grids is 10 and 4, respectively. For a 100% sash opening area, 40 grid cell points were measured. For 75%, 50%, and 25% openings, 30, 20, and 10 points were measured, respectively. To ensure data repeatability, the complete grid measurement sequence for each sash opening height was repeated across three independent runs (N=3), and the overall mean face velocity was calculated. Mean face velocity increased from 0.53 m/s at 100% opening to 0.80 m/s for 75%, 1.38 m/s at 50%, and 2.53 m/s at 25%. The increase was consistent with the inverse relationship expected from continuity theory. A power law regression gave $V = 0.353\ A^{-1.119}$ with $R^2 = 0.9847$. The exponent was close to the theoretical value of -1. The difference indicates that the actual airflow did not behave as a perfectly constant airflow. The results also show that reducing the sash opening position substantially increases the air velocity. This finding provides a simple practical demonstration of how opening size could affect airflow velocity. Rather than claiming measured empirical learning gains, this activity provides an adaptable instructional framework designed to enhance conceptual understanding of engineering control principles through hands-on measurement.

**Keywords:** Constant air volume fume hood, face velocity, sash opening, continuity equation, industrial hygiene

## INTRODUCTION

Laboratory fume hoods are important local exhaust ventilation devices used to capture and remove hazardous airborne contaminants generated during laboratory work. Their performance depends on the movement of air through the hood opening and on the ability of the system to maintain inward airflow under operating conditions. Current laboratory ventilation guidelines consider face velocity an important performance parameter but also clarify that face velocity alone is not a complete measure of containment. Hood performance is influenced by airflow distribution, room conditions, cross-drafts, hood geometry, user activities and other factors (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2016; Tseng et al., 2010; Zhang et al., 2024; Zhang et al., 2025).

For Industrial Hygiene students, the concept of airflow through a fume hood provides a useful connection between fluid mechanics and engineering control practice. The continuity equation is commonly introduced as Q = AV, where Q is volumetric airflow rate. A is cross-sectional area and V is average air velocity. When Q is

constant, the equation can be rearranged to V = Q/A. Therefore, velocity is theoretically inversely proportional to area. Although this relationship is straightforward mathematically, students may find it difficult to visualize how changing the sash opening area produces a measurable change in face velocity in a real engineering control device. A practical experiment that allows students to vary the sash opening, measure face velocity at multiple points, and compare the results with the theoretical relationship can help bridge this gap between theory and practice.

A fume hood provides a suitable practical system for demonstrating this relationship. In a constant air volume (CAV) hood, the exhaust airflow is intended to remain approximately constant (Lin et al., 2024; Zhang et al., 2025). If the sash opening is reduced while the exhaust flow is maintained, the same approximate volume of air must enter through a smaller opening. The average velocity at the opening should therefore increase. The relationship is also relevant to hood operation because sash position changes both the opening area and the airflow pattern experienced by the user (Manning et al., 2024; Tseng et al., 2010; Wang et al., 2026).

Recent work has continued to demonstrate the importance of understanding airflow behaviour at the fume hood face. Manning et al. (2024) compared experimental and computational velocity fields and showed that face velocity varies across the sash plane and is affected by static and dynamic conditions. Ahn et al. (2008) showed that sash opening and work practices can influence hood performance and contaminant leakage when other operating factors are present. Liu et al. (2020) also demonstrated that thermal effects associated with a person standing in front of a hood can affect containment. These findings show why a practical measurement exercise should not treat a fume hood as an ideal mathematical opening.

Laboratory ventilation also has an important energy dimension. Fume hoods can require substantial airflow and therefore contribute to laboratory energy consumption. Recent studies have examined the relationship between sash use, ventilation rates, energy efficiency and sustainability (Duan et al., 2023; He et al., 2021; He et al., 2022; Freese et al., 2024). The basic area-velocity relationship is therefore relevant not only to fluid mechanics but also to safe operation, engineering control and sustainable laboratory management.

The main objective of this study was to develop a practical teaching experiment to demonstrate the inverse relationship between air velocity (V) and sash opening area (A), as described by the continuity equation, Q = AV. A constant air volume (CAV) laboratory fume hood was used to investigate how changes in sash opening area affect the measured average face velocity. The experiment also aimed to compare the observed relationship with the theoretical inverse relationship and to evaluate the suitability of the activity as a practical teaching approach for Industrial Hygiene students. Grid-based measurements were used to estimate average face velocity across the sash opening rather than relying on a single measurement point.

## THEORETICAL BASIS

The continuity equation for steady incompressible airflow can be expressed as:

$$Q = AV$$

where Q is volumetric flow rate, A is the area through which air passes and V is the average velocity normal to that area. For a CAV fume hood, if the exhaust flow rate is approximately constant, the relationship becomes:

$$V = Q/A$$

This establishes an inverse relationship between opening area and average face velocity. If the opening area is reduced by one half while Q remains constant, the theoretical average velocity should approximately double. If the opening area is reduced to one quarter, the theoretical velocity should approximately increase four times. In power-law form, the relationship can be written as:

$$V = kA^n$$

where k is a constant and n is the power exponent. The ideal continuity relationship predicts n = -1. A value close to -1 would therefore indicate that the measured data follow the expected inverse relationship reasonably

well. However, the ideal model assumes that Q is constant and that the measured velocity represents the average flow through the complete opening. Real fume hoods can deviate from these assumptions because of non-uniform velocity distribution, turbulence, baffles, room air movement, hood geometry and changes in system resistance (Tseng et al., 2010; Manning et al., 2024; Liu et al., 2021).

# METHODOLOGY

## Equipment

The experiment was developed as a practical teaching activity to demonstrate the inverse relationship between average face velocity (V) and sash opening area (A), as described by the continuity equation, Q = AV. The test used a constant air volume (CAV) laboratory fume hood. The opening area was calculated as A = W × H, where W is the clear opening width and H is the sash opening height. The equipment included a measuring tape, thread, adhesive tape and a calibrated hot-wire anemometer. Face velocity was measured using a calibrated TSI Airflow Instruments Velocity Meter (Model TA430; accuracy: ±3% of reading or ±0.015 m/s). In accordance with Section 6.1.3 of ANSI/ASHRAE Standard 110-2016, 20 velocity readings were recorded at a rate of one reading per second at the centre of each grid cell, and the average was calculated for each cell. To ensure environmental control, all testing was performed in a closed laboratory to eliminate ambient cross-drafts exceeding 0.1 m/s. A grid-based method was used to estimate average face velocity across the opening (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2023).

## Experimental Procedure

The procedure had three steps: measuring the hood opening, setting up a grid, and measuring face velocity at four sash heights. The exhaust fan was operated for at least 30 minutes before measurements. This was intended to allow the system to reach a steady operating condition. The airflow rate was not measured directly; therefore, constant exhaust flow was an operating assumption rather than a verified result.

### Step 1: Dimension Measurement

The clear opening width (W) and maximum sash opening height (Hmax) were measured with a measuring tape. The hood width was 1,422 mm, and the maximum opening height was 460 mm.

### Step 2: Construction of the Physical Grid

Thread was used to mark a grid across the sash opening without placing a solid obstruction in the airflow. The grid spacing was designed not to exceed 150 mm in either direction. The same grid approach was used at each sash height, with only the active opening cells included in the measurements. Grid-based measurements are commonly used to estimate average face velocity across a hood opening (ASHRAE, 2023).

### Step 3: Face Velocity Measurement Across 4 Sash Openings

Face velocity was measured across four sash positions (100%, 75%, 50%, and 25% of maximum height) using the calibrated TSI Velocity Meter (Model TA430). At each active grid cell centre, 20 velocity readings were logged at 1-second intervals using the instrument's running average function. Once all grid points for a given sash opening height were logged (e.g., 40 points for 100% opening), the entire measurement procedure for that sash opening was repeated two additional times to complete three full replicate trials (N=3). The instrument specifications and running-average function are described in the manufacturer's operation and service manual (TSI Incorporated, 2022). The mean face velocities from the three runs were then averaged to represent the final mean face velocity for each sash position.

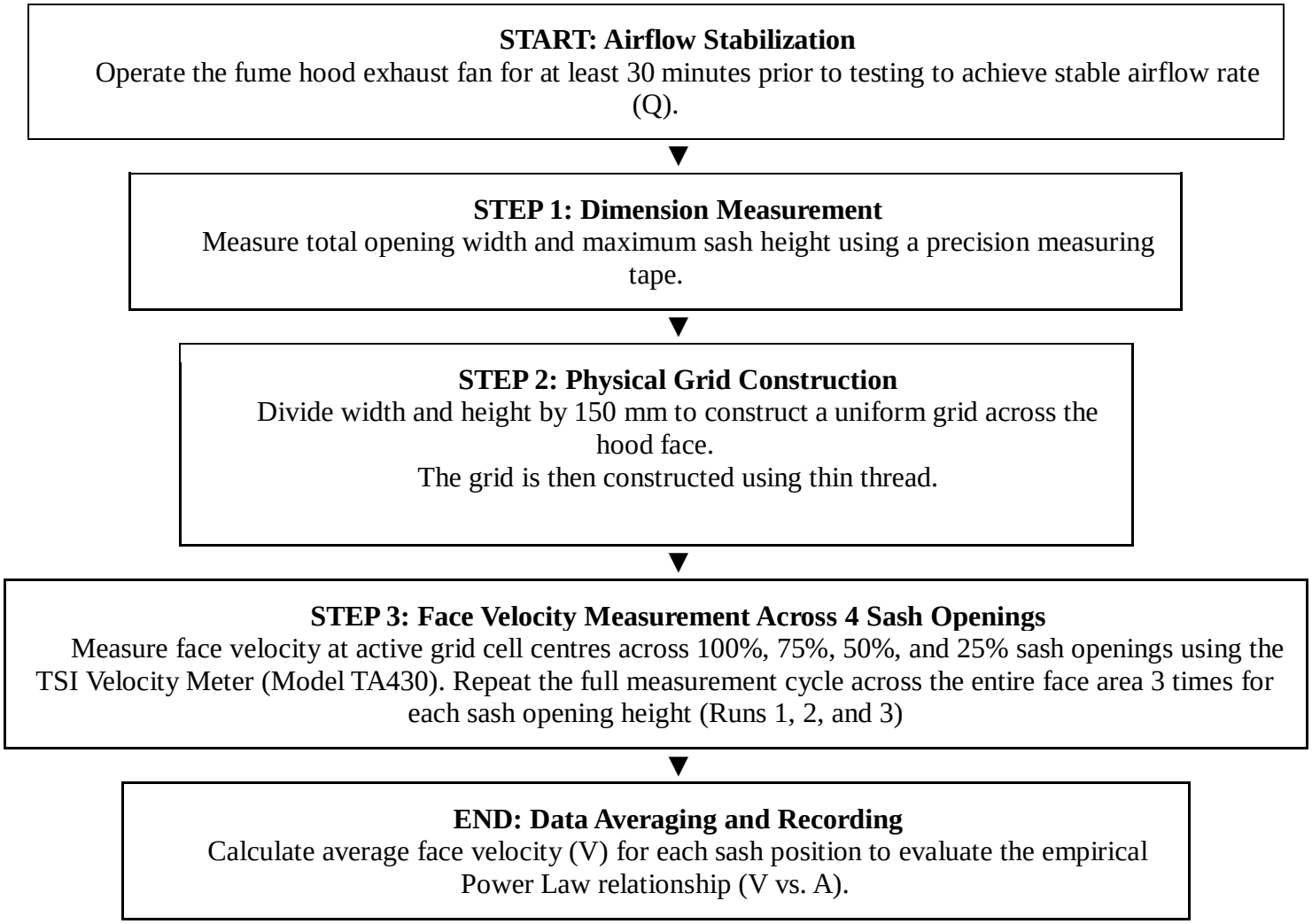



Figure 1: Sequential flowchart of the experimental procedure for fume hood face velocity measurement.

## RESULTS

The hood was located in the Chemical Laboratory, Faculty of Chemical Engineering. It's clear the opening width was 1,422 mm, and its maximum sash height was 460 mm. The opening was divided into a grid with spacing no greater than 150 mm, giving 40 measurement points at 100% opening, 30 at 75%, 20 at 50%, and 10 at 25%. Table 1 summarizes the mean face velocity at each position. Mean velocity increased as the sash opening area decreased. It rose from 0.53 m/s at full opening to 2.53 m/s at 25% opening. The calculated volumetric flow rate ranged between 0.346 $m^3/s$ and 0.451 $m^3/s$ (mean = 0.401 ± 0.044 $m^3/s$).The slight increase in Q at smaller sash openings is attributed to reduced system static pressure resistance in CAV systems, confirming that real-world operation slightly deviates from idealized constant airflow. This pattern is consistent with the inverse relationship predicted by the continuity equation when volumetric flow is approximately constant. Similar fume hood studies report that face velocity can vary across the opening and under different operating conditions (Tseng et al., 2010; Manning et al., 2024).

Table 1: Measured Data

| Sash Fraction | Sash Height, H (mm) | Face Area, A ($m^2$) | Grid Points | Average Face Velocity, V (m/s) | Estimated Flow Rate, Q = AV ($m^3/s$) |
|---|---|---|---|---|---|
| 1.00 | 460 | 0.6532 | 40 | 0.53 ± 0.04 | 0.346 |
| 0.75 | 345 | 0.4899 | 30 | 0.80 ± 0.06 | 0.392 |
| 0.50 | 230 | 0.3266 | 20 | 1.38 ± 0.09 | 0.451 |
| 0.25 | 115 | 0.1633 | 10 | 2.53 ± 0.15 | 0.413 |

### Mathematical Model (Power Law Analysis)

Figure 2 presents the relationship between mean face velocity and sash opening area. A power-law model was fitted to the four mean values:

$$V = 0.353\ A^{-1.119} \quad (1)$$

The fitted exponent was -1.119, which is close to the theoretical exponent of -1.0. The model fit was $R^2$ = 0.9847. These results show that the experiment captured the expected inverse trend. However, the high $R^2$ value does not prove that exhaust flow remained constant. The exhaust flow rate was not measured independently, and only four opening areas were tested.

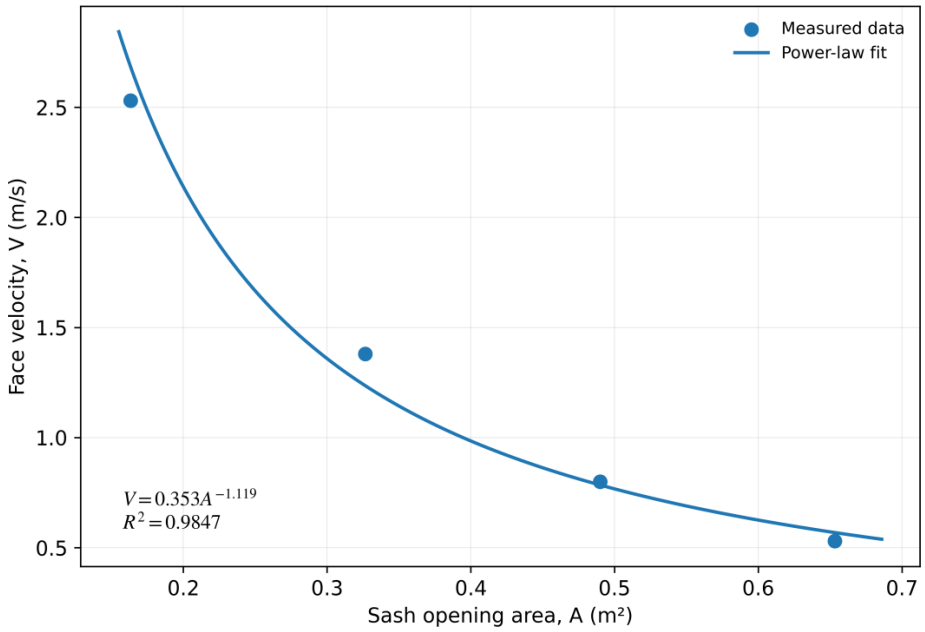



Figure 2: Graph of face velocity against sash opening area.

## DISCUSSION

### Relationship with the Continuity Equation

The main result is that mean face velocity increased as the sash opening area decreased. It rose from 0.53 m/s at 100% opening to 2.53 m/s at 25% opening. This is the trend predicted by Q = AV when Q is approximately constant. The fitted power-law exponent (-1.119) was close to the theoretical value (-1.0), so the experiment achieved its main teaching objective: it demonstrated the inverse relationship between V and A using a real engineering control device. The result should be interpreted as a practical demonstration, not proof of constant exhaust flow, because Q was not measured directly. Face velocity can also vary across the sash plane (Tseng et al., 2010; Manning et al., 2024).

### The Face Velocity and Practical Operation

The results indicate that sash position strongly affects measured face velocity. At full opening, the mean was 0.53 m/s; at 25% opening, it was 2.53 m/s. Although reducing the sash position to 25% significantly increased the face velocity to 2.53 m/s, a higher velocity does not necessarily equate to superior containment efficiency. Excessive face velocities (>1.0-1.5 m/s) can induce vortex formation and localized air turbulence at the sash edge and around the operator, potentially causing contaminants to escape. This crucial distinction reinforces the educational value of the experiment: teaching students that maintaining recommended operational sash heights (typically 0.4-0.5 m/s face velocity) balances effective containment with aerodynamic stability rather than simply maximizing face velocity.

### Pedagogical Novelty and Comparison with Existing Literature

While existing laboratory ventilation literature heavily focuses on complex computational fluid dynamics (CFD) modelling or advanced tracer gas containment testing, this study fills a distinct pedagogical gap. It provides a simple, accessible, and transparent experimental protocol that converts high-level industrial hygiene theory into an experiential laboratory module without requiring high-cost instrumentation. Rather than claiming measured empirical learning gains, this activity provides an adaptable instructional framework designed to enhance conceptual understanding of the continuity equation through hands-on data collection and limitation analysis.

### Implications for Engineering Control Equipment Education

The activity links fluid mechanics with Industrial Hygiene practice. Students measure the opening, calculate its

area, take grid-based velocity readings, calculate a mean and compare the result with the continuity equation. They can then interpret the power-law exponent and discuss why a real ventilation system may differ from an ideal model. The grid method also helps students recognize that velocity can vary across the opening. This makes the activity useful for practical teaching because students work with measurements from an actual engineering control device.

## LIMITATIONS

This study has four main limitations. First, it examined one fume hood only, so the fitted equation applies to this hood and its test conditions. Second, only four sash opening areas were tested. Third, the exhaust airflow rate was not measured directly, so the assumption of constant volumetric flow could not be verified. Fourth, the average face velocity was estimated from discrete grid points; local airflow variation may affect the estimate. Future work should measure exhaust flow at each sash position, test more opening heights, and repeat the experiment on additional CAV hoods. These steps would show whether the same model can be applied to other hoods.

## CONCLUSION

This study developed a practical teaching experiment to demonstrate the inverse relationship between fume hood sash opening area (A) and average face velocity (V). Mean velocity increased from 0.53 m/s at 100% opening to 0.80, 1.38, and 2.53 m/s at 75%, 50%, and 25%, respectively. The fitted power-law model was $V = 0.353\ A^{-1.119}$, with $R^2 = 0.9847$. The exponent was close to the theoretical value of -1.0, indicating that the measured results followed the expected inverse trend. The experiment therefore met its main teaching objective. However, the results do not confirm that exhaust flow remained constant because flow rate was not measured directly. The activity is suitable for demonstrating the continuity equation in Industrial Hygiene teaching, but it is not a substitute for a full fume hood performance or containment test. Future work should measure exhaust flow and include more sash positions and additional hoods.

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