**Duke University**

**Department of Mechanical Engineering & Materials Science**

ME 331: Thermodynamics Laboratory | Spring 2026

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# Laminar Flame Speed and Flashback Characteristics of Premixed Propane–Air Mixtures

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**Course:** ME 331 – Thermodynamics

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**Date:** Spring 2026

## Abstract

This report presents an experimental investigation of laminar flame speed in premixed propane–air mixtures through controlled flashback propagation in a vertical quartz tube. Flashback, the upstream propagation of a premixed flame through a flowing gas column, constitutes a principal safety hazard in industrial combustion systems and simultaneously provides a direct method for measuring the laminar flame speed, $S_l$, of a fuel–air mixture.

Thirteen flashback tests were conducted across a range of propane and air flow mixture rates. Premixed gas flowed upward through a quartz tube of inner diameter D = 0.545 in (13.84 mm), with the flame initiated at the top by an electric sparker. The resulting downward flashback flame was recorded with 30 fps video, with position tracked across three aluminum-tape reference marks spaced 2 inches from the top of the tube, then 3 inches from the first mark, and 4 inches from the second. Because the flame propagated downward while the gas flowed upward, the laminar flame speed was determined by the velocity addition method:

$$S_l = V_{flame} + V_{flow}$$

The propane rotameter reads in standard cubic feet per hour (SCFH); readings were converted to L/min (1 SCFH = 0.47195 L/min) before applying the air-to-propane density correction of 0.803, giving a combined conversion factor of 0.37897 L/min per SCFH for propane flow. Computed equivalence ratios ranged from 0.52 to 1.44, spanning lean through moderately rich combustion regimes. Mean laminar flame speed across the nine primary tests (excluding 4 outliers/bidirectional-propagation events) was $\overline{S}_l = 1.131 \pm 0.049$ m/s at 95% confidence.

Measured values exceed published laminar flame speeds for propane–air (reported peak ≈0.42 m/s near φ ≈1.1) by approximately a factor of 2.7. This systematic elevation is attributed to three concurrent effects: the transient over-speed of the spark-initiated ignition kernel, buoyancy-driven acceleration of the downward flame front, and the non-steady character of the flashback event. The tested equivalence ratios (φ = 0.52–1.44) were limited by the mismatch between the rotameter operating ranges and the tube geometry; the high bulk flow velocities required to sustain stable premixed delivery prevented access to leaner conditions and restricted the dataset to slightly lean through moderately rich mixtures. Two tests (6 and 9) were identified as outliers due to fume-hood air currents stalling the flame front. Two tests (10 and 12) displayed bidirectional flame propagation attributed to the sparker positioned at the tube rim. Safety measures including a flashback arrestor, check valves, and fume-hood operation were integral to the experimental design. Future improvements include a larger-diameter tube, higher-precision flow meters, and an enclosed test chamber to eliminate environmental perturbations. OBJ

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## Nomenclature

| Symbol | Description | Units |
|---|---|---|
| $A$ | Cross-sectional area of quartz tube | $m^2$ |
| $c$ | Propane rotameter correction factor (= 0.803) | — |
| $D$ | Inner diameter of quartz tube | m |
| $\Delta t_i$ | Time interval for flame to traverse segment i | s |
| $\Delta x_i$ | Physical length of measurement segment i | m |
| $(F/A)_{st}$ | Stoichiometric fuel-to-air volumetric ratio (= 0.04200) | — |
| $n_i$ | Number of video frames elapsed in segment i | frames |
| $Q_{air}$ | Volumetric flow rate of air (rotameter reading) | L/min |
| $Q_{prop}$ | Corrected volumetric flow rate of propane | L/min |
| $Q_{total}$ | Total premixed volumetric flow rate | $m^3/s$ |
| $S_l$ | Laminar flame speed | m/s |
| $V_{flame}$ | Observed flame front speed (lab frame, downward) | m/s |
| $V_{flow}$ | Bulk gas flow velocity (upward) | m/s |
| $\varphi$ | Equivalence ratio | — |
| $\sigma_z$ | Standard uncertainty of quantity z | (same units as z) |

# 1. Introduction

## 1.1 Motivation and Background

Combustion of hydrocarbon fuels in premixed burners, gas turbines, and residential heating systems introduces the hazard of flashback: the upstream propagation of a flame into a region intended to carry only unburned fuel and oxidizer. If unchecked, flashback can ignite the fuel supply line, destroy equipment, and cause explosions [1]. Preventing flashback requires knowledge of the laminar flame speed, the fundamental combustion parameter governing premixed flame propagation.

The laminar flame speed $S_l$ is defined as the velocity at which a planar flame front propagates through a premixed fuel-oxidizer mixture under laminar conditions at a specified pressure and temperature [2]. It is a thermophysical property of the mixture and depends primarily on equivalence ratio φ, reactant temperature, and pressure. For hydrocarbon fuels burned in air at ambient conditions, $S_l$ peaks slightly rich of stoichiometric and decreases toward both lean and very rich limits [3, 4].

Propane ($C_3H_8$) is widely used for residential heating, portable appliances, and laboratory research. Its complete stoichiometric combustion reaction is:

$$C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O$$

Because atmospheric air contains approximately 21% oxygen by volume, each mole of propane requires 5/0.21 = 23.81 moles of air at stoichiometric conditions, yielding a stoichiometric fuel-to-air volumetric ratio of:

$$(F/A)_{st} = 1/23.81 = 0.04200$$

The equivalence ratio φ quantifies the departure of the actual mixture from stoichiometric:

$$\varphi = (F/A)_{actual} / (F/A)_{stoich} = (Q_{prop} / Q_{air}) / 0.04200$$

Mixtures with φ < 1 are considered lean, φ = 1 are stoichiometric, and φ > 1 are rich. For propane-air, the peak laminar flame speed of approximately 0.42 m/s occurs near φ ≈ 1.05-1.1 [5, 6]. The heat of complete combustion of propane is 2,219.6 ± 0.5 kJ/mol [7].

## 1.2 Flashback Mechanism and Measurement Methodology

In a premixed burner, the gas mixture travels upward at bulk velocity $V_{flow} = Q_{total}/A$. A flame anchored at or above the tube exit burns at $S_l$ relative to the incoming gas. When $V_{flow} < S_l$, the flame cannot be sustained at its stabilization point and propagates upstream into the tube—a condition called flashback.

In the present experiment, gas flows upward through the quartz tube and the spark is applied at the top. When flashback is induced, the flame front propagates downward through the tube against the upward-flowing gas. In the reference frame of the unburned gas, the flame advances at $S_l$

downward. In the laboratory frame, the observed downward speed of the flame front ($V_{flame}$) is the intrinsic flame speed reduced by the upward gas velocity:

$$V_{flame} = S_l - V_{flow} \quad \Longrightarrow \quad S_l = V_{flame} + V_{flow}$$

This velocity addition formulation is the physically correct result when flame and bulk gas flow are anti-parallel [8, 9]. The observed downward flame speed is measured from video analysis as $V_{flame} = \Delta x_i/\Delta t_i$ averaged over three tube segments.

### 1.3 Objectives

The primary technical objectives of this investigation are:

1. Measure the lab-frame flashback flame speed across thirteen propane-air test conditions using high-speed video analysis.
2. Compute the laminar flame speed $S_l$ using the velocity addition method ($S_l = V_{flame} + V_{flow}$).
3. Quantify measurement uncertainty using Taylor-series error propagation.
4. Identify and characterize outlier and anomalous test conditions.
5. Demonstrate why the current apparatus limited access to a wider equivalence-ratio range, especially very lean and richer peak-speed conditions.

Secondary non-technical objectives include developing proficiency with rotameter flow measurement, high-speed video analysis, and the preparation of a technical report conforming to Duke MEMS standards.

# 2. Apparatus Design

### 2.1 System Overview

The experimental apparatus is a custom-built premixed burner designed to induce controlled flashback events in propane-air mixtures. The system consists of three subsystems: the gas delivery and metering system, the quartz-tube combustion chamber, and the ignition and observation system.



**Figure 1:** *Assembled flashback apparatus. Propane and air are metered independently, mixed at a Y-junction, and supplied upward through the quartz tube. Three aluminum-tape reference marks are visible on the tube exterior. Not included with the apparatus is the air compressor, which is disconnected.*

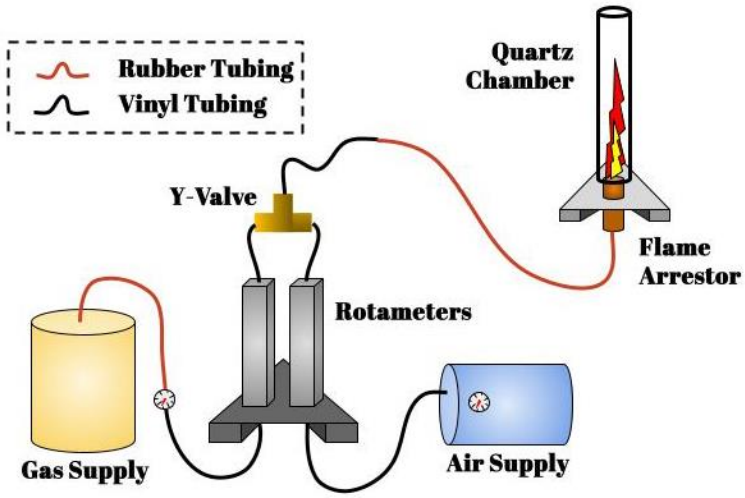



**Figure 2:** *Schematic of the gas delivery and combustion system. Arrows indicate flow direction. Safety devices (flashback arrestor and check valves) appear between the propane source and the mixing junction. [Path: Propane cylinder → rubber hose → flashback arrestor & check valve → FL4212-V rotameter → Y-valve; Air compressor → air regulator → Omega FL-2043 rotameter → Y-valve → quartz tube (upward flow) → open top with sparker.]*

### 2.2 Gas Delivery System

Propane was supplied from two Bernzomatic 14.1 oz cylinders and delivered through a small-range rotameter (FL4212-V, 0–5 SCFH range, factory-calibrated for air). The propane flow rate was converted from SCFH to L/min and corrected for propane density using a combined factor of 0.37897 L/min per SCFH (Section 3.1). Air was supplied by a laboratory compressor routed through a pressure regulator and a large-range rotameter (Omega FL-2043, 0–50 L/min, pre-calibrated for air). The two streams were combined at a brass Y-valve. A flashback arrestor and two independent check valves on the propane line prevented flame propagation into the fuel supply.

### 2.3 Combustion Chamber

The combustion chamber consisted of a transparent quartz tube mounted vertically on a 3D-printed base frame with three adjustable leveling feet. Quartz was selected for its high-temperature resistance (>1600 °C), optical transparency for video observation, and chemical inertness. The tube inner diameter is D = 0.545 in (13.84 mm) and the length accommodates three measurement segments totaling 9 in below the spark site.

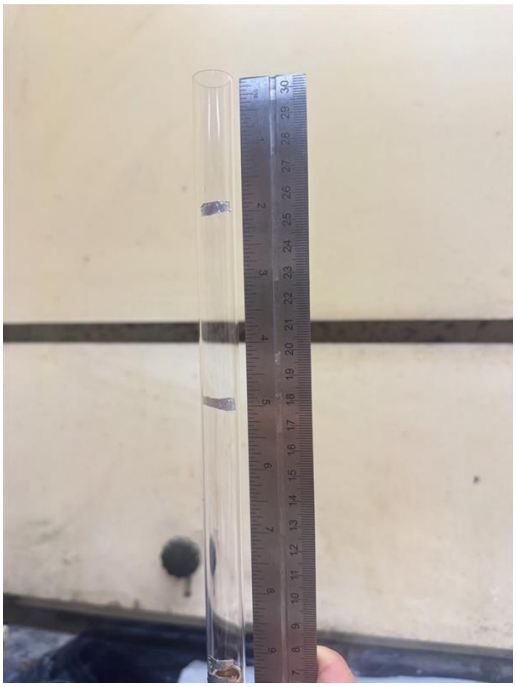


**Figure 3:** *Quartz tube with three aluminum-tape reference marks. Gas flows upward; the sparker electrode is positioned at the top (open) end.*

Three aluminum foil tape strips were affixed to the tube exterior at the following positions measured downward from the spark site:

| Segment | Description | Length $\Delta x_i$ from previous |
|---|---|---|
| 1 | Spark site → first tape mark | 2 in (50.8 mm) (from top) |
| 2 | First tape → second tape mark | 3 in (76.2 mm) |
| 3 | Second tape → third tape mark | 4 in (101.6 mm) |
| — | Total observable distance | 9 in (228.6 mm) |

### 2.4 Ignition and Observation System

A hand-held electric sparker was used to ignite the premixed gas at the top (open) end of the quartz tube. A camera recording at 30 fps captured the flame propagation event. Frame-by-frame review of the footage yielded the number of frames $n_i$ elapsed as the flame front traversed each segment: $\Delta t_i = n_i/30$ s. All experiments were conducted within a fume hood. A Class-ABC fire extinguisher was maintained within immediate reach at all times during testing.

### 2.5 Safety Considerations

Combustion experiments present many potential safety risks, including fire hazards, flashback events or explosions, and uncontrolled propagation. To mitigate these risks, multiple precautions and protective systems were implemented to make the experiment safe.

Personal protective equipment (PPE) was required and worn at all times. All participants wore safety glasses and closed-toe shoes to protect against any scattering debris, heat exposure, or ignition in case of accident. The experiment was conducted inside of a fume hood which provided ventilation and an additional protective shield as a physical barrier between the users and the propagation setup.

Additionally, several controls were engineered directly into the experimental setup. Flame arrestors were used to prevent flashback, which is when flame propagates upstream into the fuel delivery system. These devices are critical in protecting both the equipment and the operator from hazardous pressure buildup or unintended ignition within the tubing. Additionally, across the tubing of the experimental setup, aluminum tape wrappings were applied at key connection points to help fireproof and secure the connections, and reduce the likelihood of gas leakage.

The quartz combustion chamber was surrounded by a shield wall, a ring of steel acting as a protective barrier in the event of any rupture or unintended escape of flame. This added layer of containment helped ensure that any unexpected combustion remained localized and contained.

Fire safety equipment was ensured to be readily accessible throughout the experiment. This included a fire extinguisher and fire blanket, which were kept within immediate reach, and locations verified prior to operation.

Finally, to minimize risk, an operational procedure was designed for the experiment. Within the procedure, it was noted to flush the system with air between trials (to remove residual fuel), and perform ignition using an electric sparker rather than a fuel-based lighter (to avoid introducing additional combustible material). In all, these precautions added up to significantly reduce the risk of conducting flame propagation with any likelihood of hazardous conditions or events.

# 3. Experimental Methods

### 3.1 Rotameter Calibration for Propane

The FL4212-V propane rotameter was factory-calibrated for air. Because propane is denser than air ($\rho_{prop} \approx 1.882$ kg/m³ vs. $\rho_{air} \approx 1.204$ kg/m³ at 25 °C), the rotameter float experiences a different buoyancy force, causing the instrument to over-read the true propane flow. For a float-type rotameter, the corrected flow rate of gas B when calibrated for gas A is [10]:

$$Q_B = Q_{a,read} \times \sqrt{[\,\rho_a(\rho_{float} - \rho_B) / \rho_B(\rho_{float} - \rho_a)\,]}$$

The FL4212-V rotameter scale is factory-calibrated for air and reads in SCFH. Converting to L/min (1 SCFH = 0.47195 L/min) and applying the air-to-propane density correction c = 0.803 gives a combined factor of 0.37897 L/min per SCFH, so that:

$$Q_{prop} = 0.37897 \times Q_{read}$$

The air rotameter (Omega FL-2043) required no correction.



**Figure 4**: *Air (Left) and Propane (Right) Rotameter Assembly*

### 3.2 Experimental Procedure

The experimental procedure was designed to systematically control the propane-air flow ratios, to maximize both efficiency of performing the experiment as well as the safety of the users conducting it. Flow rates were adjusted using calibrated rotameters, and flame behavior was recorded using a high-speed camera. The system was flushed between trials to minimize any residual effects from previous trials.

The flame speed was then calculated by dividing the distance traveled by the time it took, and this overall process was repeated for multiple fuel-air mixture ratios, including lean, near-stoichiometric, and rich mixtures.

The procedure followed during the experiment is outlined below:

1. Set-up experimental setup as depicted, with all parts minus the propane tank.
    a. Confirm location and access of fire blanket and extinguisher.
    b. Ensure fume hood is ventilating and opening, but cover is lowered as much as possible to maximize protective coverage.
2. Inspect all fittings, hoses, and connections for integrity. Verify the flashback arrestor and check valves are installed on the propane line.
3. Confirm the quartz tube is mounted vertically using the integrated bubble level; adjust leveling feet as necessary.
4. Ensure the fume hood sash is at the recommended operating height. Confirm that a Class-ABC fire extinguisher is within 2 m of the apparatus.
5. Measure and label distance markers on glass chamber
    a. Set up camera oriented towards experimental setup, confirming both top and bottom of the glass chamber is in frame
6. Ensure air compressor is off, valves are in correct position as follows.
    a. Propane valve CLOSED
    b. Both Rotameter valves OPEN
    c. Nozzle valve is OPEN
7. Turn on the air compressor and flush the system, visually and audibly ensure no leaks.
8. Adjust rotameter valves to both be in CLOSED position.
9. Attach the propane tank, and ensure proper fit.
10. OPEN the propane cylinder valve slowly. Set the propane rotameter to the target reading; observe the float for at least 10 s to confirm stability.
11. Set the air supply line pressure regulator to 30 psi. Set the air rotameter to the target reading (30 psi line pressure was maintained constant across all tests).
12. Visually and audibly ensure flow out of the glass chamber.
13. Confirm rotameter valves reflect desired flow rates for trial being run.
14. Allow at least 30 s for the premixed gas to flush and fill the quartz tube.
15. Start the video recording camera.
16. Touch the electric sparker briefly (no more than 0.5 s) to the interior of the top tube opening, angling the spark toward the tube center.
17. Wait for flame to fully propagate (passes three distance/reference markers or fully extinguishes).
18. CLOSE both air and propane valves.
19. Repeat steps 10-18 as desired for experimental trials.
20. When experiment is completed:
    a. Remove the propane tank.
    b. Clean up experimental setup and close fume hood.
21. Review the recorded video frame-by-frame. Record the frame numbers at which the flame front reaches each reference mark. Compute $n_i$ for each segment.

22. Record all flow meter readings and frame counts in the data log. Note any anomalies (flame stalling, bidirectional propagation, etc.).

**Safety note:** Do not lean directly over the tube during ignition. Operate the sparker at arm's length. Close gas valves before touching any part of the apparatus. Review the Safety Data Sheets in Appendix C before beginning any test.

### 3.3 Calculation Procedure

For each test, the following quantities were computed sequentially:

**Corrected propane flow:**

$$Q_{prop} = 0.37897 \times Q_{read} \quad [L/min]$$

**Equivalence ratio:**

$$\varphi = (Q_{prop} / Q_{air}) / 0.04200$$

**Bulk gas flow velocity:**

$$V_{flow} = (Q_{prop} + Q_{air}) \times 1.667 \times 10^{-5} / A$$

where $A = \pi D^2/4 = \pi(0.013843)^2/4 = 1.505 \times 10^{-4}$ m$^2$.

**Observed flame front speed (per segment):**

$$V_{flame,i} = \Delta x_i / \Delta t_i = 30 \cdot \Delta x_i / n_i$$

**Average observed flame speed:**

$$V_{flame} = (1/3) \Sigma_i V_{flame,i}$$

**Laminar flame speed (velocity addition):**

$$S_l = V_{flame} + V_{flow}$$

A fully worked example for Test 1 is provided in Appendix A.

# 4. Results

### 4.1 Computed Parameters for All Thirteen Tests

Table 1 presents all measured and derived quantities for the thirteen tests. Due to the minimum flow rates required to sustain stable premixed delivery through the apparatus, the thirteen tests were across a variety of ratios; lean and stoichiometric conditions were however harder to achieve reliably. Uncertainty values ($\pm\sigma_{S_l}$) are one-standard-deviation estimates from Taylor-series error propagation (Appendix B). * = outlier (fume-hood draft stalled flame). ** = bidirectional flame propagation.

Table 1. Experimental results for all thirteen flashback tests.

| Test | $Q_{air}$ (L/min) | $Q_{read}$ (SCFH) | $Q_{prop}$ (L/min) | $\varphi$ | $V_{flow}$ (m/s) | $V_{flame}$ (m/s) | $S_l$ (m/s) | $\pm\sigma_{sl}$ (m/s) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4.5 | 0.48 | 0.182 | 0.962 | 0.519 | 0.699 | 1.218 | 0.160 |
| 2 | 7.5 | 1.20 | 0.455 | 1.444 | 0.881 | 0.238 | 1.119 | 0.062 |
| 3 | 7.3 | 1.10 | 0.417 | 1.360 | 0.855 | 0.233 | 1.088 | 0.062 |
| 4 | 5.5 | 0.45 | 0.171 | 0.738 | 0.628 | 0.529 | 1.157 | 0.098 |
| 5 | 4.9 | 0.40 | 0.152 | 0.737 | 0.560 | 0.614 | 1.174 | 0.150 |
| 6 * | 5.5 | 0.41 | 0.155 | 0.673 | 0.626 | 0.210 | 0.836 | 0.059 |
| 7 | 6.0 | 0.50 | 0.189 | 0.752 | 0.686 | 0.505 | 1.191 | 0.096 |
| 8 | 6.4 | 0.58 | 0.220 | 0.818 | 0.733 | 0.339 | 1.072 | 0.069 |
| 9 * | 7.0 | 0.40 | 0.152 | 0.516 | 0.792 | 0.177 | 0.969 | 0.059 |
| 10 ** | 5.8 | 0.55 | 0.208 | 0.856 | 0.666 | 0.614 | 1.280 | 0.113 |
| 11 | 6.7 | 0.56 | 0.212 | 0.754 | 0.766 | 0.381 | 1.147 | 0.071 |
| 12 ** | 5.6 | 0.60 | 0.227 | 0.967 | 0.645 | 0.525 | 1.170 | 0.095 |
| 13 | 7.0 | 0.71 | 0.269 | 0.915 | 0.805 | 0.208 | 1.013 | 0.060 |

### 4.2 Laminar Flame Speed vs. Equivalence Ratio

Figure 5 shows $S_l$ vs. $\varphi$ for all thirteen tests with one-standard-deviation error bars, across a variety of ratios. Primary tests (filled circles) cluster near $S_l \approx 1.16$ m/s. Outliers (Tests 6, 9) shown as triangles; bidirectional-propagation tests (10, 12) shown as squares. The dashed reference line marks the published peak $S_l$ for propane-air near $\varphi \approx 1.1$ (~0.42 m/s) [5].

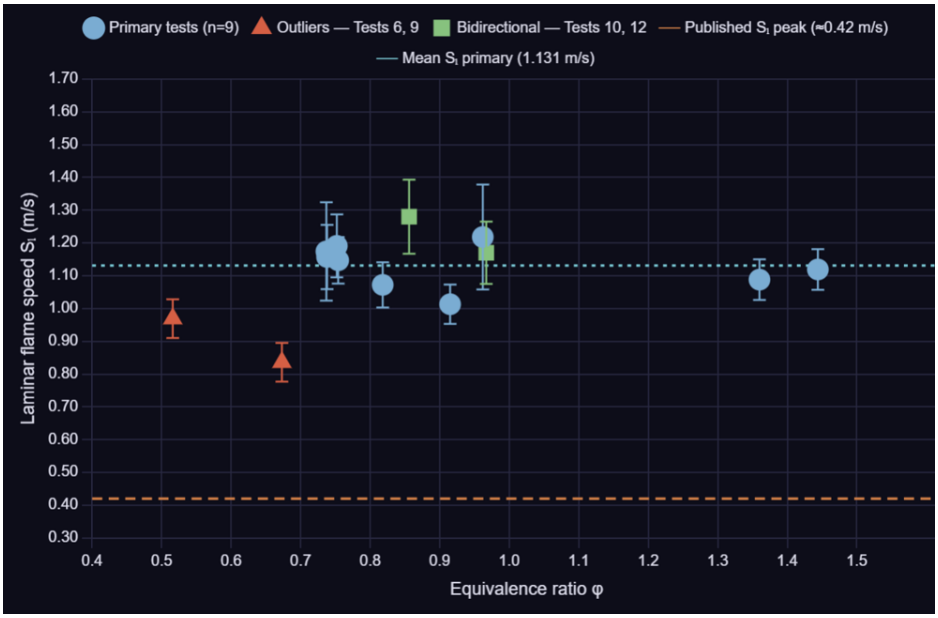



**Figure 5:** *Laminar flame speed $S_l$ vs. equivalence ratio φ for all 13 tests, with one-standard-deviation error bars. The dashed line marks the published peak $S_l$ for propane-air (≈0.42 m/s near φ ≈1.1). Measured values exceed the published peak by approximately a factor of 2.7.*

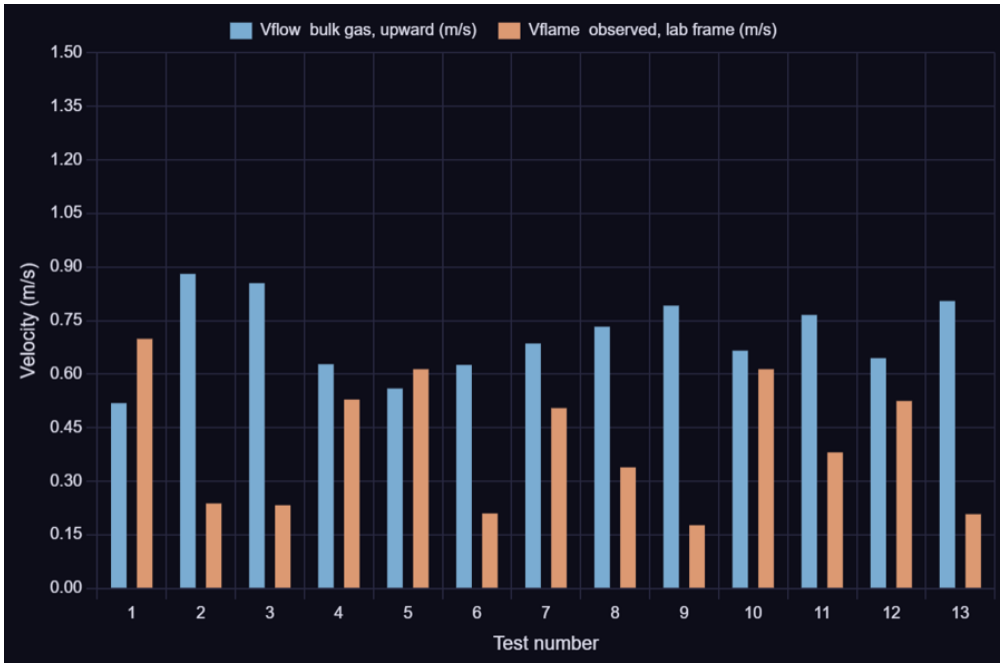



**Figure 6:** *Bulk gas flow velocity $V_{flow}$ and observed lab-frame flame front velocity $V_{flame}$ for all 13 tests.*

### 4.3 Statistical Summary

Excluding Tests 6 and 9 (outliers) and Tests 10 and 12 (bidirectional), the nine primary tests yield:

| Statistic | Value |
|---|---|
| Sample size n | 9 |
| Mean $\overline{S}_l$ | 1.131 m/s |
| Sample standard deviation s | 0.064 m/s |
| Standard error of mean s/√n | 0.021 m/s |
| 95% CI ($t_{8,0.025} = 2.306$) | 1.131 ± 0.049 m/s |
| Range | 1.013 – 1.218 m/s |
| Coefficient of variation | 5.7% |

## 5. Discussion

### 5.1 Different Ratio Regimes

All thirteen tests produced equivalence ratios spanning $\varphi \in [0.52, 1.44]$, covering lean, near stoichiometric, and moderately rich combustion regimes in line with the experimental intent. The corrected range results directly from properly converting the FL4212-V rotameter reading from SCFH to L/min before applying the density correction. This can be demonstrated quantitatively. The propane volumetric flow rate is:

$$Q_{prop} = 0.803 \times 0.47195 \times Q_{read,SCFH} = 0.37897 \times Q_{read,SCFH}\ [L/min]$$

Since $\varphi$ scales linearly with $Q_{prop}$ for fixed $Q_{air}$, every equivalence ratio in the original calculation was inflated by exactly $1/0.47195 \approx 2.12$. This shifts the apparent all-rich dataset ($\varphi \in [1.09, 3.06]$) into the correct lean-to-moderately-rich range ($\varphi \in [0.52, 1.44]$). The equivalence ratio is defined as:

$$\varphi = (Q_{prop} / Q_{air}) / f_{stoich}$$

where $f_{stoich} = 0.042$ is the stoichiometric volumetric fuel-to-air ratio for propane (derived from $C3H8 + 5O2 \rightarrow 3CO2 + 4H2O$ with air at 21% O2 by volume). A test reaches stoichiometric ($\varphi = 1$) when $Q_{prop} = 0.042 \times Q_{air}$, or equivalently when:

$$Q_{read,stoich} = 0.042 \times Q_{air} / 0.37897 = 0.1109 \times Q_{air}\ [SCFH, \text{ with } Q_{air} \text{ in L/min}]$$

At the lowest tested air flow rate ($Q_{air} = 4.5$ L/min), stoichiometric requires $Q_{read} = 0.499$ SCFH. As a representative example, Test 1 used $Q_{read} = 0.48$ SCFH and $Q_{air} = 4.5$ L/min, giving:

$$\varphi = (0.37897 \times 0.48 / 4.5) / 0.042 = 0.04042 / 0.042 = 0.962$$

Every test with $Q_{read}$ below the stoichiometric threshold for its air flow rate produced a lean mixture. Seven of the nine primary tests fell at or below stoichiometric ($\varphi \leq 0.97$), and two extended into the moderately rich regime ($\varphi = 1.36$–$1.44$, Tests 2 and 3) or just above stoichiometric ($\varphi = 0.967$, Test 12). The two leanest tests (Tests 6 and 9, $\varphi = 0.673$ and 0.516) are excluded from the primary analysis (Section 5.3). The nine primary tests span $\varphi = 0.74$–$0.97$, clustering in the slightly lean regime where published data indicate the Sl–$\varphi$ curve is relatively flat [5], consistent with the low observed scatter (CV = 5.7%). A future experiment extending to higher propane flow rates or lower air flow rates would shift the dataset toward richer conditions and more fully resolve the peak of the Sl–$\varphi$ curve near $\varphi \approx 1.1$.

### 5.2 Systematic Offset from Published Values

The mean measured $S_l = 1.131$ m/s exceeds the published maximum laminar flame speed for propane-air (≈0.42 m/s) by a factor of ≈2.7. Three mechanisms likely contribute to this systematic elevation:

**1. Transient ignition over-speed.**

The electric spark deposits finite energy into the gas, creating a hot ignition kernel that propagates faster than the steady-state laminar burning velocity. The kernel decelerates toward the true $S_l$ over a distance that can be much longer than the 9-inch observation window. Ignition kernels have been reported to travel at two to four times the quiescent $S_l$ before decaying to steady propagation [11, 1]. Since the entire measurement window may lie within this transient over-speed region, the computed $S_l$ values are expected to overestimate the steady-state laminar flame speed.

**2. Buoyancy-driven enhancement.**

Hot combustion products ($T \approx 2000$ K) are roughly 6.7 times less dense than the ambient premixed gas. As the flame propagates downward (the flashback direction), the buoyant products exert an upward pressure on the flame interface. The reaction force accelerates the flame downward, effectively increasing the observed propagation rate beyond the quiescent $S_l$. This effect is absent in standard $S_l$ measurement methods that use upward-propagating or stabilized flames and is not captured by the one-dimensional velocity addition formula [1, 2].

**3. Tube geometry and wall effects.**

In a tube of finite diameter, the flame front adopts a curved (parabolic or tulip) shape rather than the idealized planar geometry assumed in the laminar flame speed definition. Heat loss to the tube wall reduces the local burning rate near the wall while the center advances rapidly. The measured mark-to-mark propagation speed is a spatially averaged quantity that does not distinguish between these regions [11]. Despite the absolute offset, the nine primary tests cluster within a narrow range ($s = 0.064$ m/s, CV = 5.7%), confirming reproducible ignition and propagation conditions.

### 5.3 Outlier Tests: Tests 6 and 9

Tests 6 and 9 produced $S_l$ values of 0.836 m/s and 0.969 m/s, respectively—14 to 26% below the primary-test mean. In both, the third measurement segment showed anomalously long propagation times ($n_3 = 25$ frames and 23 frames respectively, compared to typical 4–7 frames per segment). This is consistent with the flame stalling or nearly extinguishing in the lower portion of the tube. The most probable cause is aerodynamic perturbation from the fume-hood sash—cross-directional air currents that can disrupt the flame front in the lower segments where the flame has decelerated due to wall heat loss and mixture dilution. These tests are excluded from the primary statistical analysis but retained in Table 1 for completeness.

### 5.4 Bidirectional Flame Propagation: Tests 10 and 12

Tests 10 and 12 displayed simultaneous downward flame propagation inside the tube and upward flame propagation above the tube opening. The attributed cause is that the electric sparker was held at the tube rim rather than inside the tube. This produced an ignition event at the interface between the exiting premixed gas and the ambient air above. The resulting flame ball propagated radially in all directions: downward into the tube (the measured flashback event) and upward into the free gas above the opening. Although the measured downward propagation in these tests is physically real, the boundary condition at the ignition site differs from the other eleven tests. These

tests are excluded from the primary analysis. In future experiments, the sparker should be mounted on a fixed bracket positioned consistently inside the tube.

### 5.5 Comparison with Cooper Union Reference Data

The Cooper Union ME160 study [9] conducted a similar flashback experiment with propane-air in a quartz tube. Their reported flame speeds at peak equivalence ratio ranged from approximately 60–100 cm/s (0.60–1.00 m/s), measured as raw lab-frame speeds without applying the velocity addition correction. Because their gas flow rates were significantly lower (12–18 mL/s vs. approximately 75–125 mL/s in this study), their bulk flow velocities were correspondingly smaller. When the gas flow correction is omitted from the present data (using only $V_{flame}$ as the reported speed), the present lab-frame speeds of 0.18–0.70 m/s fall within the same order of magnitude as the Cooper Union results, supporting consistency of the two datasets at a qualitative level.

### 5.6 Usage of Mean Laminar Flame Speed versus Peak Laminar Flame Speed

While the initial objective of this study was to identify the peak laminar flame speed as a function of equivalence ratio, the analysis was ultimately shifted toward the use of the mean laminar flame speed. This change was driven by several limitations in the dataset, including a relatively small number of primary trials (n = 9), limited precision in equivalence ratio control, and a narrow range of tested conditions. Across the primary tests, the measured laminar flame speeds exhibited very low variation, with values tightly clustered around the mean ($\bar{S}_l$ = 1.131 m/s, CV = 5.7%). This indicates that the experiment consistently produced nearly identical propagation speeds despite variations in equivalence ratio. Because of this strong clustering, utilizing a distinct peak in flame speed as a function of φ is not statistically meaningful within the available dataset.

As a result, comparing individual trials or attempting to identify a peak value would overinterpret small variations that fall within experimental uncertainty. Instead, the mean laminar flame speed provides a more robust and representative characterization of the system behavior under the tested conditions.

## 6. Conclusions

This investigation characterized flashback flame propagation in premixed propane-air mixtures across thirteen test conditions, with tested equivalence ratios between 0.52 and 1.44, covering lean to rich combustion regimes. Although the experiment was initially intended to cover a wider range of tested equivalence ratios, the chosen flow rates paired with the design geometry and rotameter range limited the testable conditions.

Using the velocity addition method, the laminar flame speed was measured as $S_l = 1.131 \pm 0.049$m/s (95% confidence) across the nine primary tests. The relatively low spread in the data (coefficient of variation of 5.7%) indicates that the experimental setup at least produced consistent and repeatable flame propagation behavior under similar conditions.

The measured flame speeds were significantly higher than previously published values for propane-air mixtures, which typically have a laminar flame speed of 0.42 m/s near stoichiometric conditions. This difference between experimental and published values is likely due to several non-ideal effects noticed during the experiment, including the transient over-speed of the ignition kernel, buoyancy-driven acceleration of the downward-propagating flame, and the curved flame geometry inside the tube. These factors would cause the measured values to reflect a non-steady flashback process rather than the true laminar flame velocity.

A small number of tests were excluded from the analysis. Tests 6 and 9 showed reduced flame speeds due to apparent flame stalling, likely caused by airflow disturbances from the fume hood. Tests 10 and 12 exhibited bidirectional flame propagation, which was traced back to inconsistent sparker positioning at the tube entrance. Excluding these cases, the remaining data shows strong internal consistency.

Overall, the experiment successfully demonstrated controlled flashback behavior and provided meaningful insight into how flame propagation can depend on flow conditions and mixture composition. While the experimentally measured values differ from ideal laminar flame speeds, the trends observed are physically consistent and well explained by the experimental conditions. With future improvements (described below), this setup has the potential to produce more accurate measurements across a wider range of equivalence ratios.

### Future Improvements

While the experiment successfully demonstrated controlled flashback behavior and provided consistent measurements of flame propagation, several improvements could be made to enhance the accuracy and capability of the experiment.

The first major limitation identified in the study was the mismatch between the rotameter operating ranges and the geometry of the combustion tube. The rotameters available for the experiment at the time of design operated at relatively high volumetric flow rates, which forced the overall system to output at high bulk velocity, and led to the restriction of equivalence ratios, and a loss

of precision. Future work should be conducted with lower-range, higher-precision flow meters, which would allow for finer control of propane and air flow rates and enable finer control near stoichiometric conditions and access to a broader range of lean and rich mixtures. Increased precision would also lead to reduced uncertainty and potential error in ratio and velocity calculations.

Changing the geometry of the combustion chamber to better match the existing rotameter capacity is another potential approach to future experiments. By increasing the inner diameter of the tube, the bulk gas velocity for any given flow rates would be reduced, which would allow flashback to occur at lower equivalence ratios. This would be a more complicated change because the mounting and burner system would have to be redesigned to ensure proper flow alignment and maintain structural integrity.

The combustion tube was observed to become extremely hot between experimental trials, leading to the identification of thermal effects within the tube as a potential source of error. Future designs should consider using a combustion tube with thicker walls, or an implementation of active cooling to reduce temperature flare-ups.

Another important change for future iterations of the experiment is suggested by the flame behavior near the base of the combustion tube, where the flame flickered or became stationary. A more controlled quenching region—either through material selection or another method—would improve the safety of the experiment by eliminating persistent flames that remained after trials.

Finally, improvements in the measurement tools used for the experiment would even further increase accuracy. A higher frame-rate camera would reduce uncertainty in the timing of flame tracking. Separately, improved mounting of the sparker would ensure consistent ignition conditions and eliminate the multi-directional propagation effects observed in certain trials.

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## Appendix A Sample Calculations (Test 1)

**Given:** $Q_{air}$ = 4.5 L/min, $Q_{read}$ = 0.48 SCFH, n = [2, 4, 4] frames for segments 1, 2, 3.

**Step 1: Corrected propane flow rate.**

$$Q_{prop} = c \times Q_{read} = 0.37897 \times 0.48 = 0.18191 \text{ L/min}$$

**Step 2: Equivalence ratio.**

$$\varphi = (0.18191 / 4.5) / 0.04200 = 0.04042 / 0.04200 = 0.962 \rightarrow \text{Lean}$$

**Step 3: Tube cross-sectional area.**

$$A = \pi D^2/4 = \pi(0.545 \times 0.0254)^2/4 = \pi(0.013843)^2/4 = 1.505\times10^{-4} \text{ m}^2$$

**Step 4: Bulk gas flow velocity.**

$$Q_{total} = (0.18191 + 4.5) \times 1.667\times10^{-5} = 7.804\times10^{-5} \text{ m}^3/\text{s}$$

$$V_{flow} = 7.804\times10^{-5} / 1.505\times10^{-4} = 0.519 \text{ m/s}$$

**Step 5: Observed flame front speed (per segment).**

$$V_{flame,1} = 0.0508 \text{ m} / (2/30 \text{ s}) = 0.762 \text{ m/s}$$

$$V_{flame,2} = 0.0762 \text{ m} / (4/30 \text{ s}) = 0.572 \text{ m/s}$$

$$V_{flame,3} = 0.1016 \text{ m} / (4/30 \text{ s}) = 0.762 \text{ m/s}$$

**Step 6: Average observed flame speed.**

$$V_{flame} = (0.762 + 0.572 + 0.762) / 3 = 0.699 \text{ m/s}$$

**Step 7: Laminar flame speed (velocity addition).**

$$S_l = V_{flame} + V_{flow} = 0.699 + 0.519 = 1.218 \text{ m/s}$$

## Appendix B Error Analysis and Uncertainty Propagation

Uncertainty was propagated using the Taylor-series (first-order) method. For $z = f(x_1, \ldots, x_n)$ [12]:

$$\sigma_{z}^2 = \Sigma_i (\partial z/\partial x_i)^2 \sigma_{xi}^2$$

**Elemental uncertainties:**

| Source | Symbol | Value |
|---|---|---|
| Propane rotameter (1% of 5 SCFH range) | $\sigma_{Qp}$ | 0.05 SCFH |
| Air rotameter (1% of 50 L/min range) | $\sigma_{Qa}$ | 0.50 L/min |
| Tube inner diameter (±0.005 in) | $\sigma_D$ | 0.127 mm |
| Video frame count (±1 frame at 30 fps) | $\sigma_t$ | 0.033 s |
| Reference mark position (±1/16 in) | $\sigma_x$ | 1.59 mm |

**Uncertainty in tube area:**

$$\sigma_A = (\pi D/2)\sigma_D = (\pi \times 0.013843/2) \times 1.27 \times 10^{-4} = 2.76 \times 10^{-6}\ m^2$$

**Uncertainty in bulk flow velocity:**

Let $k = 1.667 \times 10^{-5}$ m³/(L/min). Then $V_{flow} = (Q_p + Q_a)k/A$:

$$\sigma_V = \sqrt{[(k/A)^2\sigma_{Qp}^2 + (k/A)^2\sigma_{Qa}^2 + (Q_{total} \cdot k/A^2)^2\sigma_{A}^2]}$$

For Test 1: $\sigma_V = 0.056$ m/s.

**Uncertainty in observed flame speed:**

For each segment i: $V_{flame,i}^2 = \Delta x_i^2/\Delta t_i^2$:

$$\sigma_{Vf,i} = \sqrt{[(1/\Delta t_i)^2\sigma_x^2 + (\Delta x_i/\Delta t_i^2)^2\sigma_t^2]}$$

For the three-segment average: $\sigma_{Vf}^2 = (1/9)\Sigma_i\sigma_{Vf,i}^2$. For Test 1: $\sigma_{Vf} = 0.150$ m/s.

**Uncertainty in laminar flame speed:**

$$\sigma_{Sl} = \sqrt{[\sigma_{Vf}^2 + \sigma_V^2]}$$

For Test 1: $\sigma_{Sl} = \sqrt{(0.150^2 + 0.056^2)} = 0.160$ m/s.

**Uncertainty in equivalence ratio:**

$$(\sigma_\varphi/\varphi)^2 = (\sigma_{Qp}/Q_p)^2 + (\sigma_{Qa}/Q_a)^2$$

For Test 1: $\sigma_\varphi = 0.962 \times \sqrt{[(0.05/0.48)^2 + (0.50/4.5)^2]} = 0.147$.

## Appendix C Safety Information

**Safety Data Sheet: Propane ($C_3H_8$) — GHS / OSHA HazCom 2012**

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**SECTION 1 — Identification**

Product name: Propane (Liquefied Petroleum Gas, LPG) Chemical formula: $C_3H_8$ CAS No.: 74-98-6 UN No.: 1978

**SECTION 2 — Hazard Identification**

GHS Classification: Flammable gas Category 1 (H220); Compressed gas (H280); Simple asphyxiant. Signal word: DANGER
Hazard statements: H220 — Extremely flammable gas. H280 — Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation.
Precautionary statements: P210 — Keep away from heat, sparks, open flames, and hot surfaces. P377 — Leaking gas fire: do not extinguish unless leak can be stopped safely. P381 — Eliminate all ignition sources if safe to do so. P403 — Store in a well-ventilated place.

**SECTION 3 — Composition / Information on Ingredients**

| Component | CAS No. | Formula | Concentration |
|---|---|---|---|
| Propane | 74-98-6 | $C_3H_8$ | ≥95% v/v |
| Propylene | 115-07-1 | $C_3H_6$ | ≤5% |
| Butane | 106-97-8 | $C_4H_{10}$ | ≤2% |

**SECTION 4 — First Aid Measures**

Inhalation: Remove to fresh air immediately. If breathing is difficult give oxygen. If not breathing, apply artificial respiration. Seek medical attention.
Skin contact: Liquid propane causes cryogenic burns (frostbite). Warm affected area gently with lukewarm water; do not rub. Seek medical attention.
Eye contact: Flush with water for 15 minutes. Seek medical attention. Ingestion: Not applicable (gas under normal conditions).
Note to physician: High concentrations may cause CNS depression; cardiac arrhythmias have been reported following massive exposures.

**SECTION 5 — Firefighting Measures**

Suitable media: $CO_2$, dry chemical, water fog. Do not direct water jets on burning gas.

**SECTION 6 — Accidental Release Measures**

Eliminate all ignition sources. Ensure adequate ventilation. If safe, stop leak by closing the valve. Do not use electrical equipment in the spill area. Evacuate from downwind areas. Contact

emergency services if release cannot be controlled. Propane vapor is heavier than air and accumulates in low-lying areas.

**SECTION 7 — Handling and Storage**

Handling: Use only in well-ventilated areas. Bond and ground containers during transfer. Install a flashback arrestor and check valves when connected to laboratory apparatus. Storage: Store cylinders upright, secured against tipping, in a cool, dry, well-ventilated area away from heat sources (<40 °C) and oxidizers. Maximum storage temperature: 52 °C. Comply with NFPA 58 [14].

**SECTION 8 — Exposure Controls / Personal Protection**

OSHA PEL: 1000 ppm TWA (Simple Asphyxiant). ACGIH TLV: Simple Asphyxiant. Engineering controls: Use only in a well-ventilated fume hood. Install gas detectors if bulk quantities are stored.
PPE: Safety glasses, lab coat, heat-resistant gloves when handling cylinders.

**SECTION 9 — Physical and Chemical Properties**

Appearance: Colorless, odorless gas (commercial grade has odorant added). MW: 44.10 g/mol. BP: −42.1 °C. Vapor pressure: 8.4 bar at 20 °C. Vapor density (air=1): 1.52. Flash point: −104 °C. Flammable limits: LEL 2.1% – UEL 9.5% v/v. Auto-ignition temperature: 470 °C.

**SECTION 10 — Stability and Reactivity**

Stability: Stable under normal conditions. Conditions to avoid: Heat, open flames, sparks, static discharge. Incompatible materials: Strong oxidizers. Hazardous decomposition: CO, $CO_2$, unburned hydrocarbons under incomplete combustion.

**SECTION 11 — Toxicological Information**

Acute toxicity: Simple asphyxiant at high concentrations (>10%). No known chronic toxicity. Not listed as a carcinogen by IARC, NTP, or OSHA. Primary route of exposure: inhalation.

**SECTION 12 — Ecological Information**

Environmental fate: Propane is a greenhouse gas (GWP ≈ 3.3 over 100 years). Does not persist in soil or water. Not classified as hazardous to aquatic environment.

**SECTION 13 — Disposal Considerations**

Do not vent unburned propane to atmosphere in confined spaces. Return empty cylinders to supplier. Contact local environmental authority for large-scale disposal.

**SECTION 14 — Transport Information**

UN Number: 1978. Proper shipping name: Propane. Hazard class: 2.1 (Flammable Gas). ERG Guide: 115. DOT label: Flammable Gas.

**SECTION 15 — Regulatory Information**

OSHA: Covered under 29 CFR 1910.119 (PSM) above threshold quantities. EPA: Listed as VOC precursor. NFPA 58: Governs storage and handling of LP gas. California Prop 65: Not listed.

**SECTION 16 — Other Information**

SDS revision date: 2024. Prepared for academic laboratory use in compliance with OSHA HazCom 2012 (29 CFR 1910.1200) and GHS Revision 7. Emergency: CHEMTREC 1-800-424-9300 (24 hr).

Data source: Physical and chemical property data (Sections 7-9) sourced from the NIST Chemistry WebBook, National Institute of Standards and Technology, U.S. Department of Commerce [15].

**Safety Data Sheet: Compressed Air — GHS / OSHA HazCom 2012**

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**SECTION 1 — Identification**

Product name: Compressed Air (Instrument Grade / Industrial) CAS No.: 132259-10-0 UN No.: 1002

Supplier: Laboratory compressor / Airgas (or equivalent) Emergency: CHEMTREC 1-800-424-9300

Intended use: Oxidizer source for premixed propane-air combustion laboratory experiment.

**SECTION 2 — Hazard Identification**

GHS Classification: Compressed gas (H280); supports combustion (oxygen content). Signal word: WARNING

Hazard statement: H280 — Contains gas under pressure; may explode if heated. Precautionary statements: P410 — Protect from sunlight. P403 — Store in a well-ventilated place. P260 — Do not breathe high-pressure air directly from cylinder.

**SECTION 3 — Composition / Information on Ingredients**

| Component | CAS No. | Formula | Concentration |
|---|---|---|---|
| Nitrogen | 7727-37-9 | $N_2$ | ~78% v/v |
| Oxygen | 7782-44-7 | $O_2$ | ~21% v/v |
| Argon | 7440-37-1 | Ar | ~0.93% |
| Other gases | — | — | Balance |

**SECTION 4 — First Aid Measures**

Inhalation: High-pressure air inhalation from a pressurized source can cause pulmonary barotrauma; do not use as breathing air. If displaced atmosphere causes dizziness, remove to fresh air.

Skin contact: High-pressure air jet can cause air embolism; never direct compressed air at skin. Eye contact: Flush with water if debris introduced. Use safety glasses when connecting pneumatic lines.

**SECTION 5 — Firefighting Measures**

Compressed air supports combustion but is not flammable. Do not use air cylinders near fire if integrity is uncertain. Cool cylinders with water if exposed to fire. Shut off air supply if possible.

**SECTION 6 — Accidental Release Measures**

If a compressed-air line fails, the sudden release is a noise and kinetic hazard (whiplash). Evacuate the immediate area. Shut off the compressor. Inspect fittings before reconnecting.

**SECTION 7 — Handling and Storage**

Handling: Inspect hoses and fittings before each use. Do not exceed rated pressure of rotameters, hoses, or fittings.
Storage: Compressors and receiver tanks should be inspected annually. Store in a well-ventilated area. Drain moisture from receiver tank regularly.

**SECTION 8 — Exposure Controls / Personal Protection**

OSHA PEL: Oxygen must constitute ≥19.5% of breathing atmosphere; compressed ambient air meets this criterion.
PPE: Safety glasses mandatory. Hearing protection if operating compressor in enclosed space.

**SECTION 9 — Physical and Chemical Properties**

Appearance: Colorless, odorless gas. MW (avg.): 28.97 g/mol. Non-flammable; supports combustion. Vapor density (air=1): 1.00.

**SECTION 10 — Stability and Reactivity**

Stability: Stable. Incompatible materials: Oils and greases near high-pressure oxygen content (fire/explosion hazard). Hazardous decomposition products: None under normal conditions.

**SECTION 11 — Toxicological Information**

No toxicity from ambient-composition air. Nitrogen is a simple asphyxiant if $O_2$ is displaced below 19.5%. Not a carcinogen.

**SECTION 12 — Ecological Information**

Air release is environmentally neutral at ambient composition. No persistence or bioaccumulation. Not classified as hazardous to aquatic environment.

**SECTION 13 — Disposal Considerations**

Vent excess compressed air slowly in a well-ventilated outdoor area, away from personnel. Ensure compressor is de-energized before servicing. No special waste classification required.

**SECTION 14 — Transport Information**

UN Number: 1002. Proper shipping name: Air, compressed. Hazard class: 2.2 (Non-flammable, non-toxic gas). ERG Guide: 122.

**SECTION 15 — Regulatory Information**

OSHA: 29 CFR 1910.134. NFPA 704: Health 0, Flammability 0, Instability 0, Special OX. Not listed under CERCLA, SARA, or California Prop 65.

**SECTION 16 — Other Information**

SDS revision date: 2024. Prepared for academic laboratory use in compliance with OSHA HazCom 2012 (29 CFR 1910.1200) and GHS Revision 7. Emergency: CHEMTREC 1-800-424-9300 (24 hr).

## Appendix D Bill of Materials

| Item | Function | Specification | Qty |
|---|---|---|---|
| Quartz tube | Combustion chamber | ID 0.545 in, OD ~0.625 in, 18 in L | 1 |
| Bernzomatic 14.1 oz propane cylinder | Fuel supply | CGA 600, 14.1 oz | 2 |
| Omega FL-2043 rotameter | Air metering | 0-50 L/min, air-calibrated | 1 |
| FL4212-V rotameter | Propane metering | 0-5 SCFH, air-calibrated | 1 |
| Brass Y-valve | Gas mixing | 1/4 in NPT, brass | 1 |
| Flashback arrestor | Propane line safety | 1/4 in NPT, stainless | 1 |
| Check valve | Backflow prevention | 1/4 in NPT | 2 |
| Electric sparker | Ignition | Piezo trigger | 1 |
| 3D-printed base frame | Tube support | PLA, adjustable feet | 1 |
| Camera (30 fps) | Flame observation | Min. 1080p, 30 fps | 1 |
| Aluminum foil tape | Reference marks | 1 in wide | 1 roll |
| CGA 600 regulator | Cylinder pressure regulation | 0-30 psig output | 1 |
| Rubber hose, 1/4 in ID | Gas line | Propane-rated | 2 ft |
| Class-ABC fire extinguisher | Emergency response | 2.5 lb minimum | 1 |
| PTFE thread-seal tape | Thread sealing | 1/2 in wide | 1 roll |

[15] National Institute of Standards and Technology, NIST Chemistry WebBook, SRD 69. U.S. Department of Commerce, Gaithersburg, MD. Available: https://webbook.nist.gov/chemistry/

## Appendix E Rotameter Industry Sheets

### Appendix E.1 Industry sheet for FL-4212-V rotameter:

# OEM-STYLE ACRYLIC VARIABLE AREA FLOW METER

***Capacities: Water: 6.5 GPH to 20 GPM***
***Air: 2 SCFH to 40 SCFM***

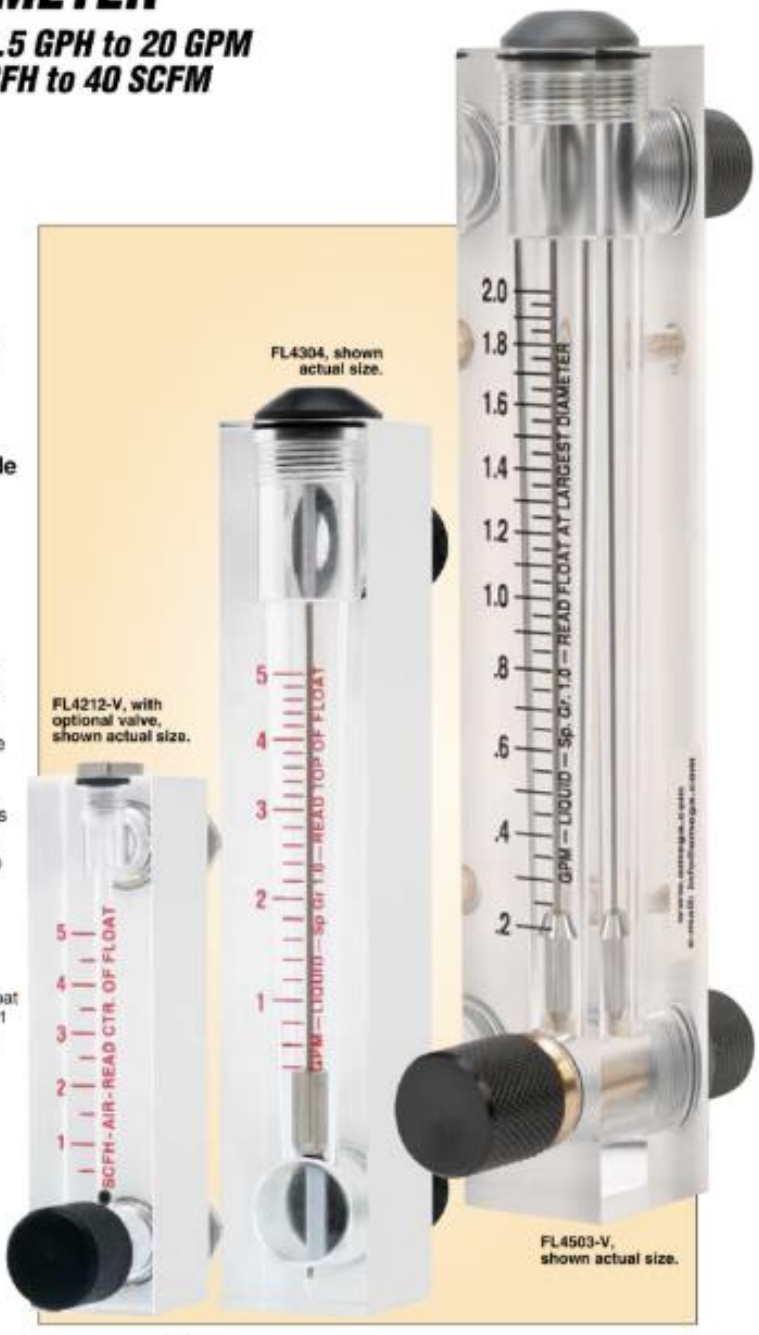
## FL4000 Series

1 YEAR WARRANTY · NIST · RoHS

Optional

- 50, 75, 127, and 250 mm (1.97, 2.96, 5, and 9.85") Scale Lengths
- Floats are Rod-Guided in Most Models
- Metering Valves Available
- Rear Inserts Provided for Panel Mounting
- Direct-Reading Scales

FL4000 OEM-style variable area flow meter are precisely machined from solid acrylic blocks. They are available in 50, 75, 127, and 250 mm (1.97, 2.96, 5, and 9.85") scale lengths and have accuracies between 2 and 6%. Designed for front-panel mounting, the rear ports extend through the panel for easy hookup. Mounting threads are also provided. Units are available with and without valves.




### SPECIFICATIONS

**Construction:** Acrylic tube, 316 SS float and guide rod (no guide rod for FL4211 through FL4215 air meters), PVC end fittings (brass on FL4200 Series), EPR O-rings, optional brass valve

**Max Pressure/Temperature:**

**Water Ranges:**
125 psig @ 21°C (70°F);
54°C (130°F) at 0 psig

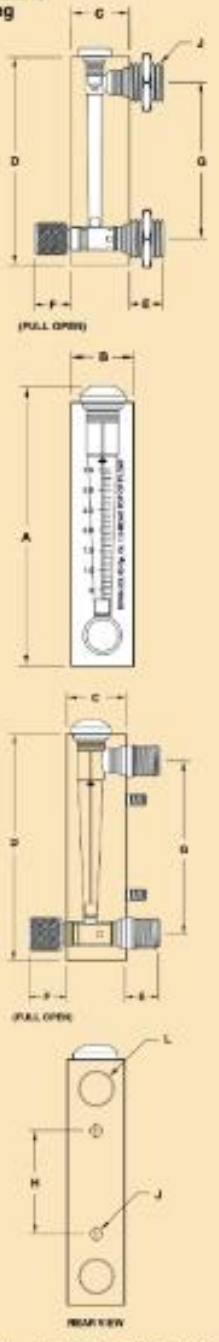
**Air Ranges:**
100 psig @ 21°C (70°F);
38°C (100°F) @ 0 psig

**Full Scale Accuracy/Repeatability:**

**FL4200:** 6/2%
**FL4300 and FL4400:** 4/1%
**FL4500:** 3/1/2%
**FL4600:** 2/1/2%

B-17a

**Dimensional Drawing**




**Connection:** FL4200: ¼ FNPT; FL4300 and FL-4500: ⅜ FNPT x ½ MNPT; FL4400: 1 MNPT; FL4600: ½ FNPT




B1

| Dimensions mm (inch) | FL4200 | FL4300 | FL4400 | FL4500 | FL4600 |
|---|---|---|---|---|---|
| A | 102 (4.0) | 168 (6.6) | 225 (8.9) | 210 (8¼) | 362 (14¼) |
| B | 25 (1.0) | 32 (1.3) | 44 (1.8) | 32 (1¼) | 44 (1¾) |
| C | 32 (1.3) | 35 (1.4) | 46 (1.9) | 35 (1⅜) | 46 (1 13/16) |
| D | 105 (4.1) | 173 (6.8) | 232 (9.9) | 213 (8⅜) | 368 (14½) |
| E | 13 (0.5) | 25 (1.0) | 32 (1.3) | 25 (1) | 19 (¾) |
| F | 29 (1.1) | 32 (1.3) | 48 (1.9) | 32 (1¼) | 48 (1⅞) |
| G | 76 (3.0) | 127 (5.0) | 165 (6.5) | 164 (6 7/16) | 311 (12¼) |
| H | — | 76 (3.0) | 102 (4.0) | 100 (3 15/16) | 222 (8¾) |
| L | 17 (0.7) | 25 (1.0) | 35 (1.4) | 25 (1) | 32 (1¼) |
| J Mounting Thread Size* | † | ¼ x 20 | ¼ x 20 | ¼ x 20 | ⅜ x 24 |

** Threaded stud.*

*† FL4200 has ¼" hex lock nuts around ports; requires ½" holes to be drilled through the panel.*

## To Order

| Water | | | | Air | |
|---|---|---|---|---|---|
| Model No. | Range (Maximum)* | Pressure Drop, inH2O** | | Model No. | Range (Maximum)* |
| | | No Valve | Valve | | |
| FL4201 | 7 GPH | 1** | 1.3** | FL4211 | 2.6 SCFH |
| FL4202 | 12 GPH | 15** | 17** | FL4212 | 5.0 SCFH |
| FL4203 | 22 GPH | 35** | 51** | FL4213 | 10.0 SCFH |
| FL4204 | 44 GPH | 149** | 200** | FL4214 | 20.0 SCFH |
| FL4205 | 60 GPH | 100** | 250** | FL4215 | 30.0 SCFH |
| FL4301 | 1 GPM | 18** | 26** | FL4216 | 60.0 SCFH |
| FL4302 | 2.0 GPM | 70** | 125** | FL4217 | 100.0 SCFH |
| FL4303 | 3.5 GPM | 200** | 290** | FL4218 | 180.0 SCFH |
| FL4304 | 5 GPM | 290** | 440** | FL4219 | 4.0 SCFM |
| FL4401 | 10 GPM | 53 | 220 | FL4411 | 40.0 SCFM |
| FL4402 | 15 GPM | 132 | 330 | FL4412 | 62.0 SCFM |
| FL4403 | 20 GPM | 200 | 400 | — | — |
| FL4501 | 1 GPM | 18 | 33 | FL4511 | 4.0 SCFM |
| FL4502 | 100 GPH | 45 | 75 | FL4512 | 6.8 SCFM |
| FL4503 | 2 GPM | 70 | 155 | FL4513 | 8.0 SCFM |
| FL4504 | 5 GPM | 240 | 400 | FL4514 | 20.0 SCFM |
| FL4601 | 2 GPM | 5 | 21 | FL4611 | 8.5 SCFM |
| FL4602 | 3.5 GPM | 13 | 50 | FL4612 | 14.5 SCFM |
| FL4603 | 5 GPM | 20 | 95 | FL4613 | 20.0 SCFM |
| FL4604 | 10 GPM | 110 | 270 | FL4614 | 40.0 SCFM |

*Comes complete with operator's manual.*

** Minimum flow rate = 10% of maximum flow rate listed.*

*** For water ranges. For air ranges, contact the Flow Department. For units with brass valve, add suffix "-V" to model number, additional cost for FL4200s, FL4300s, FL4400s, FL4500s and FL4600s.*

*For NIST calibration certificate, add "**-NIST 5PT**" to the model number for 5-point calibration, or "**-NIST 10PT**" for 10-point calibration for additional cost.*

***Ordering Examples: FL4303-V**, acrylic variable area flow meter, 3.5 GPM flow rate.*

***FL-4613**, acrylic variable area flow meter, 40 SCFM max flow.*

B-17b

**Appendix E.2 Industry sheet for Omega FL-2043 rotameter:**

# ACRYLIC FLOWMETERS

B

## FL-2000 Series

- Easy-to-Read English or Metric Scales
- Water Ranges from 4 CCM to 20 GPM, Air Ranges from 40 CCM to 4000 LPM
- Threaded Brass Inserts for Quick Installation
- Easy Disassembly and Assembly for Maintenance
- Durable One-Piece Clear Acrylic Construction
- Stable, Easy-to-Read Float
- Superior Quality

### APPLICATIONS

- Air Sampling Equipment
- Aquaculture
- Desalinization Equipment
- Gas Analyzers
- Medical Systems
- Photo Processing Equipment
- Water Treatment and Distribution Systems




FL-2013 Air, shown smaller than actual size.




FL-2080-NV Water, shown smaller than actual size.

The FL-2000 Series offers a wide variety of precision flowmeters for use in medical, industrial, chemical, and laboratory applications at an economical price. Units are available with or without valves.

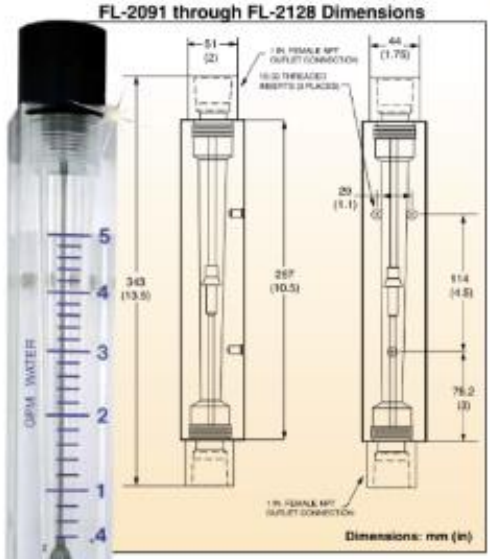
### SPECIFICATIONS

**Accuracy:**
Models FL-2001–FL-2025: ±5% F.S.
Models FL-2031–FL-2099: ±3% F.S.
Models FL-2071–FL-2128: ±2% F.S.
**Float:** Black glass stainless steel
**Body:** Clear acrylic
**Seals:** Buna "O" Rings with brass or PVC fittings FKM "O" Rings with stainless steel fittings
**Pressure:** 100 psig max. @ 21°C (70°F)
**Temperature:**
65°C (150°F) max @ 0 psig

**Fittings:** Brass std; stainless steel optional except for FL-2071 through FL-2128, which have 1 NPT PVC fittings only
**Valves:** Models FL-2001 through FL-2099: brass standard; stainless steel cartridge type (optional)
**FL-2071 through FL-2128:** Optional plastic in-line gate

B-15a

**FL-2091 through FL-2128 Dimensions**




**FL-2097, shown smaller than actual size**

**FL-2091 through FL-2128 Dimension**

| In Line | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Millimeters** | 343 | 50.8 | 267 | 25.4 | 28.6 | 44.5 | 114 | 76.2 |
| **Inches** | 13.5 | 2.0 | 10.5 | 1 FNPT | 1.1 | 1.8 | 4.5 | 3.0 |

**Accuracy: ±2% Full Scale In-Line**

| To Order | |
|---|---|
| **Model No.** | **Range SCFM of Air** |
| FL-2091 | 3 to 25 |
| FL-2092 | 4 to 50 |
| FL-2093 | 10 to 100 |
| | **Range LPM of Air** |
| FL-2094 | 100 to 700 |
| FL-2095 | 100 to 1400 |
| FL-2096 | 400 to 4000 |
| | **Range GPM of Water** |
| FL-2097 | 0.4 to 5 |
| FL-2098 | 1 to 10 |
| FL-2099 | 2 to 20 |
| | **Range LPM of Water** |
| FL-2126 | 1 to 19 |
| FL-2127 | 4 to 36 |
| FL-2128 | 5 to 75 |

*Units are standard without valves.*

*To order with plastic integral gate valve, add suffix **"-V"** to model number for additional cost for FL-2090 Series, and FL-2120 Series.*

*For optional 10-point NIST certificate add suffix, **"-NIST"** to the model number, for additional cost and two weeks to the standard lead time.*

***Ordering Example: FL-2095,** flow meter, 100 to 1400 LPM Air*
***FL-2127-V,** flow meter, 4 to 36 LPM water, with valves.*

**Accuracy: ±2% Full Scale Panel Mount**

| To Order | |
|---|---|
| **Model No.** | **Range SCFM of Air** |
| FL-2071 | 3 to 25 |
| FL-2072 | 4 to 50 |
| FL-2073 | 10 to 100 |
| | **Range LPM of Air** |
| FL-2074 | 100 to 700 |
| FL-2075 | 100 to 1400 |
| FL-2076 | 400 to 3400 |
| | **Range GPM of Water** |
| FL-2077 | 0.6 to 5 |
| FL-2078 | 1 to 10 |
| FL-2079 | 2 to 20 |
| | **Range LPM of Water** |
| FL-2080 | 2 to 19 |
| FL-2081 | 4 to 36 |
| FL-2082 | 5 to 75 |

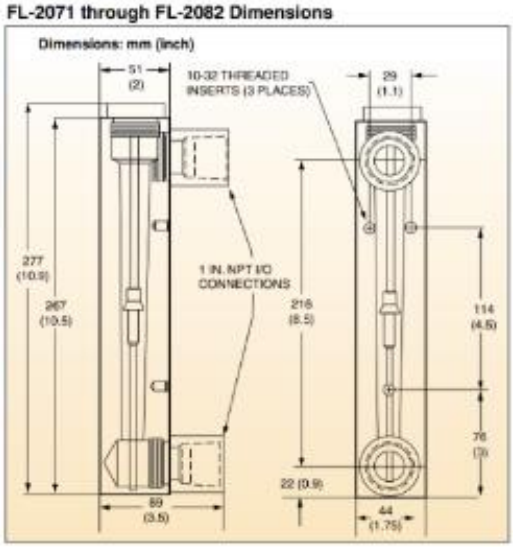
*Units come complete with operator's manual.*
*Units are standard without valves.*

*To order with plastic integral gate valve, add suffix **"-V"** to model number for additional cost.*

*For optional 10-point NIST certificate add suffix, **"-NIST"** to the model number for additional cost and two weeks to the standard lead time.*

***Ordering Examples: FL-2075,** flow meter valve, 100 to 1400 LPM air.*
***FL-2080,** flow meter valve, 2 to 19 LPM water.*

**FL-2071 through FL-2082 Dimensions**




| PANEL MOUNT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Millimeters** | 273 | 267 | 50.8 | 25.4 | 216 | 22.2 | 114 | 76.2 |
| **Inches** | 10.9 | 10.5 | 2 | 1 FNPT | 8.5 | 0.9 | 4.5 | 3 |




FL-2060, Air, shown smaller than actual size.




FL-2066-NV, shown smaller than actual size.

**Accuracy: ±3% Full Scale Panel Mount**

| To Order | |
|---|---|
| **Model No.** | **Range SCFM of Air** |
| FL-2060 | 0.5 to 5 |
| FL-2061 | 1 to 10 |
| FL-2062 | 4 to 20 |
| | **Range LPM of Air** |
| FL-2063 | 14 to 140 |
| FL-2064 | 30 to 300 |
| FL-2065 | 100 to 560 |
| | **Range GPM of Water** |
| FL-2066 | 0.25 to 2.5 |
| FL-2067 | 0.4 to 5 |
| | **Range LPM of Water** |
| FL-2068 | 1 to 10 |
| FL-2069 | 2 to 20 |

*Units come standard with brass valves and operator's manual.*
*Dual scales supplied std: SCFM/SCFH, GPM/GPH and LPM/LPH*
*To order with stainless steel valve, add suffix "**-SS**" to model number for additional cost.*
*To order without a valve, add suffix "**-NV**" to model number and subtract from cost.*
*For optional 10-point NIST certificate add suffix, "**-NIST**" to the model number, for additional cost and two weeks to the standard lead time.*
***Ordering Examples:** **FL-2060**, flow meter with brass valve, 0.5 to 5 SCFM.*
***FL-2069-NV**, flow meter no valve 2 to 20 LPM.*

| To Order | |
|---|---|
| **Model No.** | **Range SCFH of Air** |
| FL-2031 | 0.4 to 5 |
| FL-2032 | 1 to 10 |
| FL-2033 | 2 to 20 |
| FL-2034 | 4 to 40 |
| FL-2035 | 10 to 100 |
| FL-2036 | 14 to 150 |
| FL-2037 | 20 to 200 |
| | **Range CCM of Air** |
| FL-2038 | 100 to 1000 |
| | **Range LPM of Air** |
| FL-2039 | 0.4 to 5 |
| FL-2040 | 1 to 10 |
| FL-2041 | 2 to 20 |
| FL-2042 | 3 to 30 |
| FL-2043 | 4 to 50 |
| FL-2044 | 10 to 100 |
| | **Range CCM of Water** |
| FL-2045 | 4 to 50 |
| FL-2046 | 10 to 120 |
| FL-2047 | 25 to 225 |
| FL-2048 | 40 to 400 |
| FL-2049 | 40 to 660 |
| FL-2050 | 100 to 1500 |
| FL-2051 | 200 to 3000 |
| FL-2052 | 300 to 3700 |
| | **Range GPH of Water** |
| FL-2053 | 1 to 10 |
| FL-2054 | 2 to 25 |
| FL-2055 | 4 to 50 |
| FL-2056 | 6 to 60 |
| | **Range SCFM of Air** |
| FL-2057 | 0.3 to 3 |

*Units come standard with brass valves and operator's manual.*
*To order with stainless steel valve, add suffix "**-SS**" to model number for additional cost.*
*To order without a valve, add suffix "**-NV**" to model number and subtract from cost.*
*For optional 10-point NIST certificate add suffix, "**-NIST**" to the model number, for additional cost and two weeks to the standard lead time.*
***Ordering Examples:** **FL-2035**, economical flow meter, with brass valve, 14 to 150 SCFH Air.*
***FL-2036-NV**, economical flow meter, without brass valve, 14 to 150 SCFH Air.*



FL-2091, Air, shown smaller than actual size.

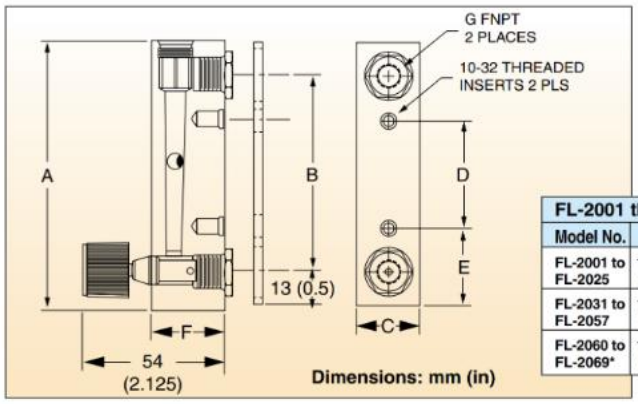


FL-2053, Water, shown smaller than actual size.



FL-2041-NV, shown smaller than actual size.

B




**FL-2001 through FL-2069 Dimensions mm (inch)**

| Model No. | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| FL-2001 to FL-2025 | 102.0 (4.0) | 76.2 (3.0) | 25.4 (1) | 41.3 (1.6) | 30.2 (1.2) | 28.6 (1.1) | ⅛ |
| FL-2031 to FL-2057 | 165.0 (6.5) | 140.0 (5.5) | 34.9 (1.4) | 88.9 (3.5) | 38.1 (1.5) | 28.6 (1.1) | ⅛ |
| FL-2060 to FL-2069* | 168.0 (6.6) | 140.0 (5.5) | 28.6 (1.1) | 88.9 (3.5) | 38.1 (1.5) | 34.9 (1.4) | ¼ |

**All in this range do not include a ⅛" back plate*

**Accuracy: ±5% Full Scale Panel Mount**

| To Order | |
|---|---|
| **Model No.** | **Range SCFH of Air** |
| FL-2001 | 0.1 to 1.0 |
| FL-2002 | 0.2 to 2.0 |
| FL-2003 | 0.4 to 5.0 |
| FL-2004 | 0.5 to 10.0 |
| FL-2005 | 2.0 to 20.0 |
| FL-2006 | 3.0 to 30.0 |
| FL-2007 | 4.0 to 50.0 |
| FL-2008 | 10.0 to 100.0 |
| FL-2009 | 20.0 to 200.0 |
| | **Range LPM of Air** |
| FL-2010 | 0.04 to 0.5 |
| FL-2011 | 0.1 to 1.0 |
| FL-2012 | 0.2 to 2.5 |
| FL-2013 | 0.4 to 5.0 |
| FL-2014 | 1.0 to 10.0 |
| FL-2015 | 2.0 to 25.0 |
| FL-2016 | 4.0 to 50.0 |
| FL-2017 | 10.0 to 100.0 |
| | **Range SCCM of Water** |
| FL-2018 | 5 to 50 |
| FL-2019 | 10 to 100 |
| FL-2020 | 20 to 240 |
| | **Range GPH of Water** |
| FL-2021 | 0.2 to 2.0 |
| FL-2022 | 0.4 to 5.0 |
| FL-2023 | 1.0 to 10.0 |
| FL-2024 | 2.0 to 20.0 |
| FL-2025 | 4.0 to 40.0 |

*Units come standard with brass valves and operator's manual.*
*To order with stainless steel valves, add suffix "**-SS**" to model number for additional cost.*
*To order without a valve, add suffix "**-NV**" to model number and subtract from cost.*
*For optional 10-point NIST certificate add suffix, "**-NIST**" to the model number, for additional cost and two weeks to the standard lead time.*
***Ordering Examples: FL-2005**, economical flow meter with brass valve, 2 to 20 SCFH air.*
***FL-2005-NV**, economical flow meter without valve, 2 to 20 SCFH air.*




**FL-2021-NV, Water, shown larger than actual size.**