Flashback Flame Project

ME331 – Thermodynamics

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May 1, 2026



BACKGROUND & MOTIVATION

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What is Laminar Flame Speed?

The rate at which a flame front propagates through a premixed fuel-air mixture under laminar flow. Reflects reactivity, diffusivity, and heat release.

Why Does It Matter?

Critical for engine and burner design — governs efficiency, heat output, and hazard potential. Referenced widely in engineering datasheets and safety standards.

KEY INFLUENCING FACTORS

Fuel Type

Different fuels peak at different ϕ values

Equivalence Ratio (ϕ)

Primary variable — lean, stoich, rich

Temperature

Higher temp → higher flame speed

Pressure

Higher pressure → slightly lower speed

THEORY: EQUIVALENCE RATIO & FLAME SPEED

The Equivalence Ratio (ϕ)

$\varphi = (Fuel/Air)_{actual} \div (Fuel/Air)_{stoic}$

ϕ = 1 Stoichiometric (balanced)
ϕ < 1 Lean mixture (excess air)
ϕ > 1 Rich mixture (excess fuel)



Close-up of Rotameter Stand (above)

Stoichiometric Propane Combustion (pure oxygen)

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

~21% in air

Ideally, peak flame speed occurs slightly rich (ϕ ≈ 1.05–1.1), where reaction rates and heat release are maximized.

Flashback Hazard

If surrounding gas velocity drops below the laminar burning velocity, the flame travels upstream. This event is called flashback. This poses serious safety risks and informs the design of this experiment.

EXPERIMENTAL SETUP

1. **Propane Supply**

   Gas cylinder → rubber/vinyl tubing → FL4212-V rotameter (×0.803 correction factor for propane)

2. **Air Supply**

   Electric compressor → Omega FL-2043 rotameter (pre-calibrated for air, no correction needed)

3. **Mixing**

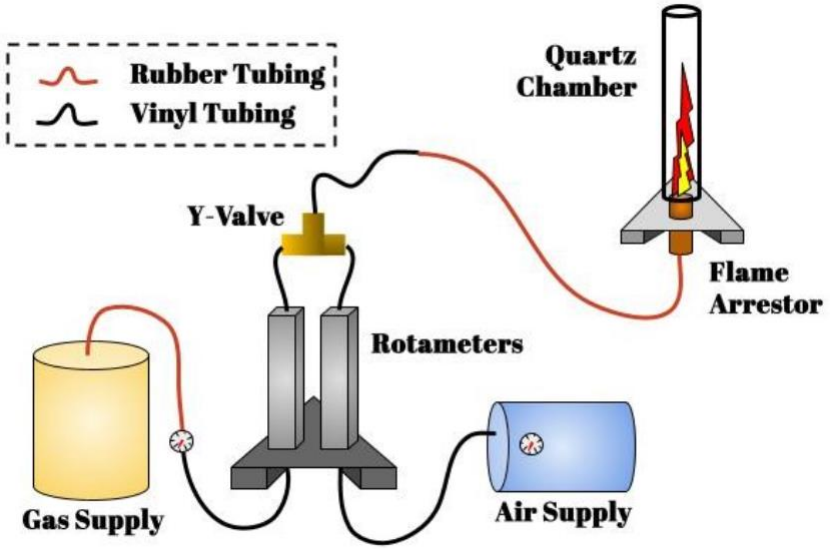
   Y-valve combines propane + air streams before entering combustion chamber

4. **Ignition**

   Electric sparker (avoids adding extra fuel that would skew mixture ratio)

5. **Measurement**

   Vertical quartz tube (pre-marked) + high-speed camera for flame tracking



Experimental Setup Diagram

EXPERIMENTAL SETUP



Physical Setup in Fume Hood



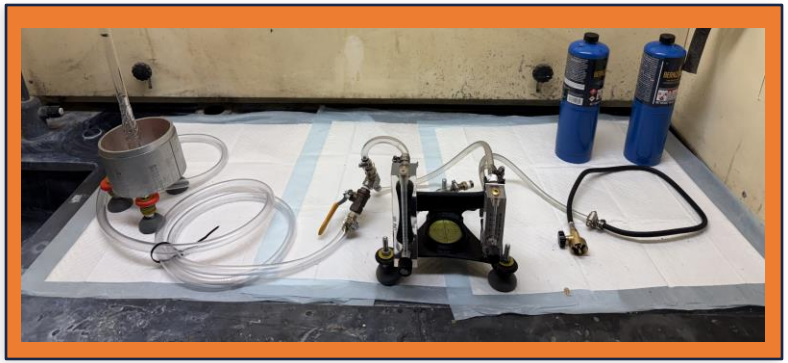
Custom Designed Stands

PROCEDURE & CALCULATION METHOD

1. Zero both rotameters before each trial
2. Set propane and air flow rates to achieve target ϕ (lean, near-stoich, or rich)
3. Allow system to purge and mix — ensures uniform pre-mixture before ignition
4. Activate camera, then ignite with electric sparker at tube top
5. Record flame travel time between pre-marked distance points on quartz tube
6. Repeat for multiple ϕ values; flush system between each trial
7. Apply 0.803 correction factor and unit conversion (1 SCFH = 0.47195 L/min) for the propane rotameter reading during data analysis

FLAME SPEED

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



TRIALS



Trial 1: Near Stoichiometric



Trial 12: Bidirectional Flame Phenomenon

RESULTS: EXPERIMENTAL DATA — ALL 13 TESTS

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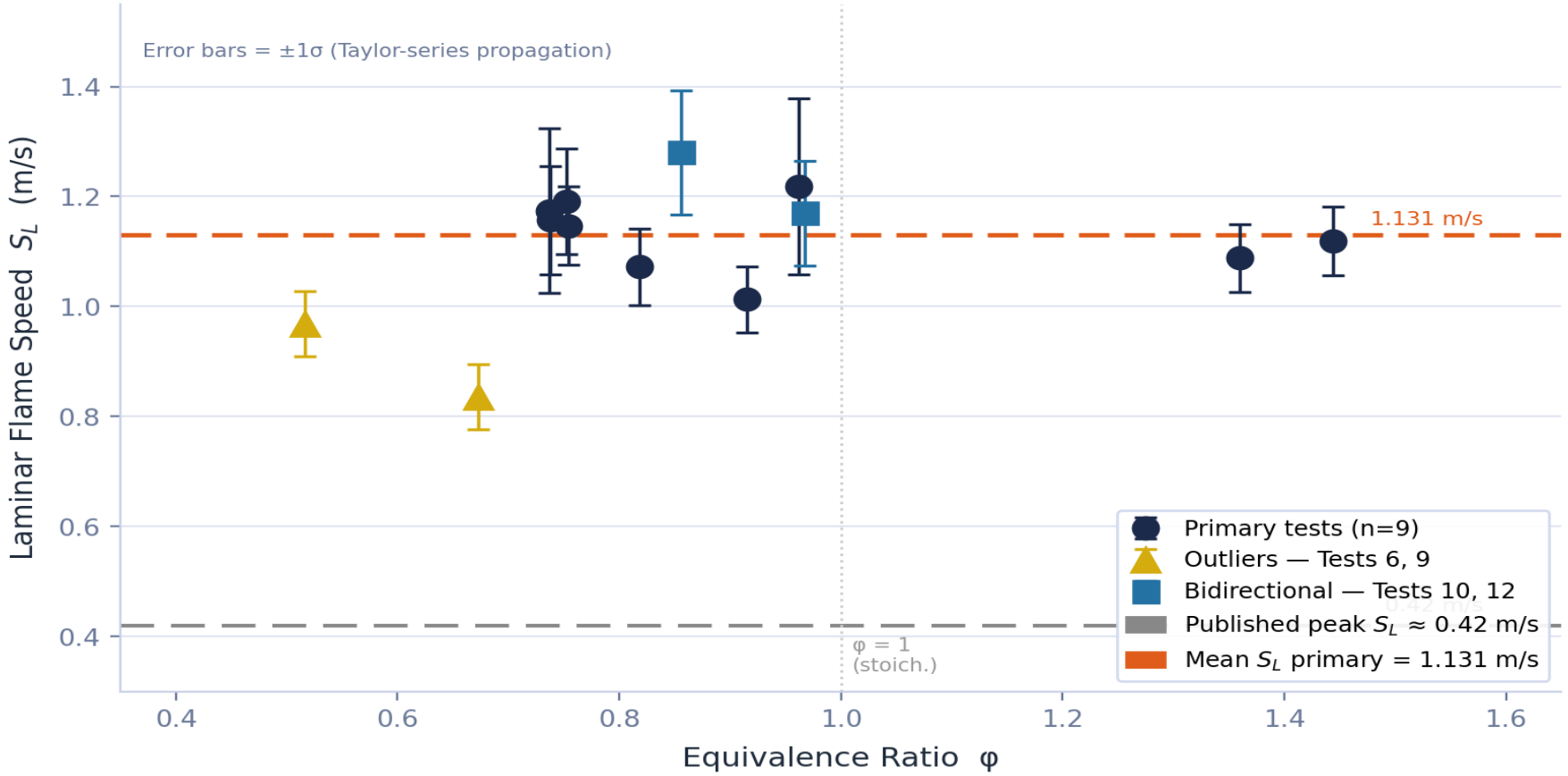
Test	Qair (L/min)	Qprop (L/min)	ϕ	Vflow (m/s)	Vflame (m/s)	Sl (m/s)	±σ (m/s)
1	4.5	0.182	0.96	0.519	0.699	**1.218**	0.160
2	7.5	0.455	1.44	0.881	0.238	**1.119**	0.062
3	7.3	0.417	1.36	0.855	0.233	**1.088**	0.062
4	5.5	0.171	0.74	0.628	0.529	**1.157**	0.098
5	4.9	0.152	0.74	0.560	0.614	**1.174**	0.150
6 *	5.5	0.155	0.67	0.626	0.210	**0.836**	0.059
7	6	0.189	0.75	0.686	0.505	**1.191**	0.096
8	6.4	0.220	0.82	0.733	0.339	**1.072**	0.069
9 *	7	0.152	0.52	0.792	0.177	**0.969**	0.059
10 **	5.8	0.208	0.86	0.666	0.614	**1.280**	0.113
11	6.7	0.212	0.75	0.766	0.381	**1.147**	0.071
12 **	5.6	0.227	0.97	0.645	0.525	**1.170**	0.095
13	7	0.269	0.92	0.805	0.208	**1.013**	0.060

* Outlier (fume-hood draft)

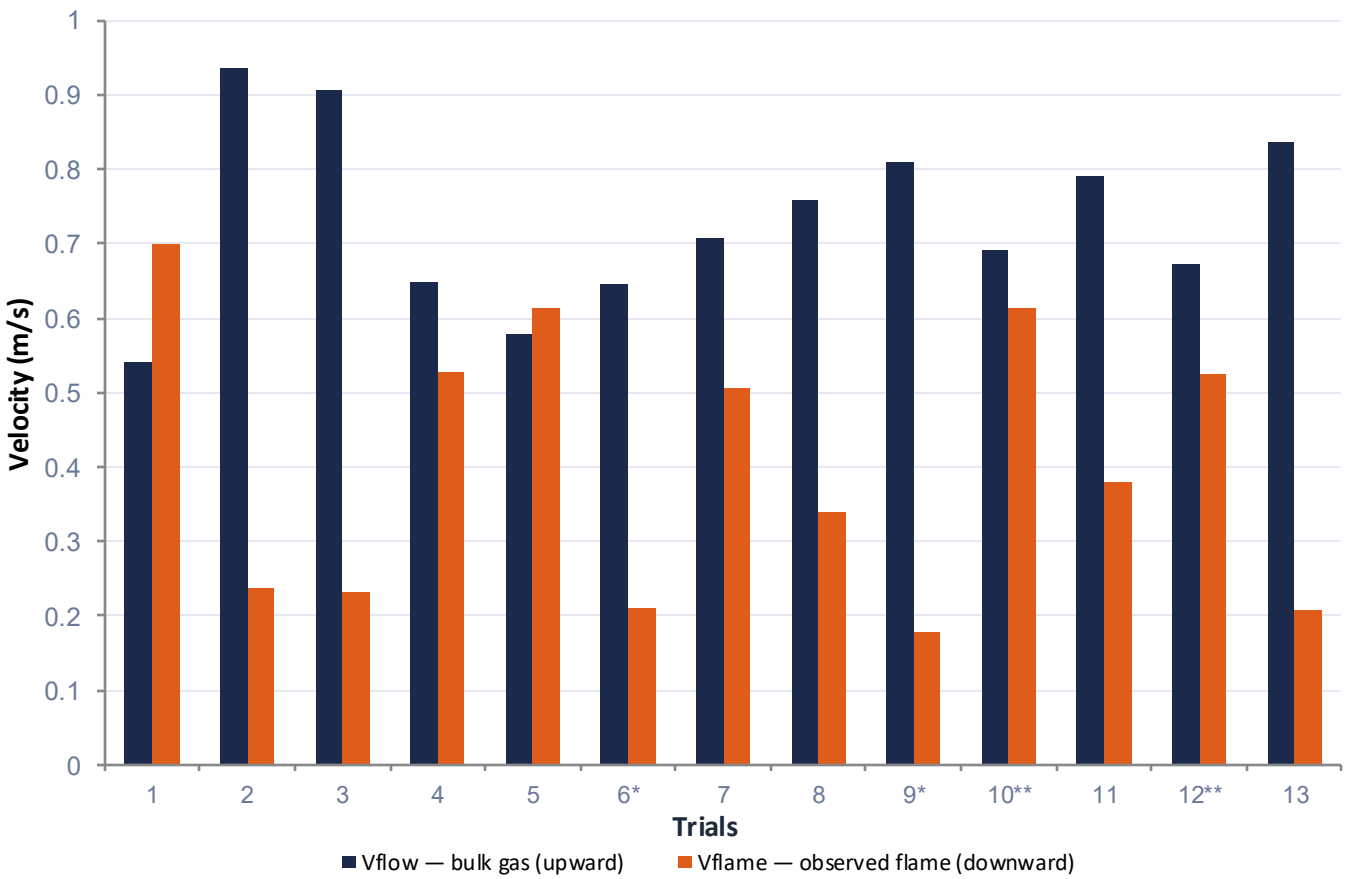
** Bidirectional flame propagation

Closest to Stoich 1:1

RESULTS: LAMINAR FLAME SPEED vs. EQUIVALENCE RATIO



RESULTS: VELOCITY COMPONENTS — V_{flow} AND V_{flame}



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

Velocity addition — anti-parallel vectors

High Q_{air} tests
V_{flow} dominates
(tests 2, 3, 9, 13)

Low Q_{air} tests
V_{flame} more visible
(tests 1, 4, 5, 7)

Sum S_l is consistently ≈ 1.10–1.24 m/s

DISCUSSION: OUTLIERS & ANOMALOUS TESTS

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Tests 6 & 9 — Outliers

Measured SI: 0.836 m/s (Test 6) | 0.969 m/s (Test 9)
18–26% below primary-test mean



Cause

Fume-hood sash cross-drafts disrupted the flame front in the lower tube segments

Tests 10 & 12 — Bidirectional Propagation

Measured SI: 1.305 m/s (Test 10) | 1.198 m/s (Test 12)



Cause

Sparker held at the tube rim created an ignition event at the interface between exiting premixed gas and ambient air. The resulting flame ball propagated in both directions.

STATISTICAL SUMMARY — PRIMARY TESTS (n = 9)

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1.162
m/s
Mean SI

±0.049
m/s
95% Confidence Interval

5.7%
CV
Coefficient of Variation

0.52–1.44
ϕ range
Lean to Moderately Rich

Statistic	Value
Sample size n	**9**
Mean SI	**1.131 m/s**
Sample std. deviation s	**0.065 m/s**
Standard error s/√n	**0.021 m/s**
95% CI (t_8 = 2.306)	**1.131 ± 0.049 m/s**
Range	**1.013 – 1.218 m/s**
Coefficient of variation	**5.7%**

ERROR PROPAGATION

Taylor-series (first-order) method

σ_{Qp} = 0.05 SCFH (1% of 5 SCFH range)

σ_{Qa} = 0.50 L/min (1% of 50 L/min range)

σ_D = 0.127 mm (±0.005 in)

σ_t = 0.033 s (±1 frame at 30 fps)

σ_x = 1.59 mm (±1/16 in)

$\sigma_{SI} = \sqrt{(\sigma Vf^2 + \sigma V^2)}$

DISCUSSION: WHY S_l EXCEEDS EXPECTED VALUES BY ~2.8×

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1

Transient Ignition Over-Speed

The spark creates an ignition kernel that propagates 2–4× faster than Sl. The observation window may lie within this over-speed region, so the full measurement reflects the kernel speed, not the true flame speed.

2

Buoyancy-Driven Acceleration

Hot combustion products are less dense than the unburned mixture; when the flame propagates downward, products push the flame, accelerating it further. Some methods use upward-propagating flames and do not capture this effect.

3

Tube Geometry and Wall Effects

The flame adopts a curved (parabolic or tulip) shape in a tube of finite diameter. Heat loss to quartz walls reduces burning rate near the wall. This can affect flame speed.



CONCLUSIONS

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01

The experiment produces consistent but elevated measurements

Tests spanned ϕ = 0.52–1.44, covering lean through moderately rich combustion. Nine primary tests ranged from ϕ = 0.74–1.36, straddling stoichiometric.

02

The overspeed error is structural, not experimental

Spark kernel transients, buoyancy-driven downward acceleration, aren't derived from experimental error

03

Quantitative result

Mean laminar flame speed:
$\bar{S}_l$ = 1.13 ± 0.05 m/s (95% CI)

Low variation (CV ≈ 5.7%) indicates strong repeatability across trials

04

Engineering takeaway / future direction

Tube diameter and flow range constrain achievable ϕ and inflate S_l

Larger tube + lower-range flow meters → access true laminar regime

FUTURE IMPROVEMENTS

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Lower-Range Flow Meters

Replace current rotameters with instruments capable of higher-precision, lower-range of volumetric flow, allowing system to output at lower bulk velocity.

Larger Tube Diameter / Active Cooling

Increase tube ID to ≥ 0.629 in to reduce bulk gas velocity at the same flow rates, and active cooling (heat sink & fans) to reduce thermal carryover between trials

Fixed Sparker Mount

Mount the electric sparker on a fixed bracket inside the tube at a consistent position to eliminate bidirectional propagation events (seen in tests 10 and 12).

Enclosed Test Chamber

Eliminate fume-hood cross-drafts by enclosing the combustion zone, removing the aerodynamic perturbations responsible for outlier tests (6 and 9).

Questions

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

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