Calorimetry of Ethanol and Methane Combustion

Measuring chemical power output for the Reactivity Rocket Project

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Year 10 Chemistry · Reactivity Rocket Project · Phase 1 Lab 2

Abstract

This investigation measures the **chemical power output** of two candidate rocket fuels — **ethanol** and **natural gas (methane)** — by burning a known mass of fuel under a water bath and recording the resulting temperature rise. The fuel-burner is reweighed after each run to obtain the fuel mass consumed, and the chemical power is computed as $P = Q/\Delta t$ where $Q = m_w c_w \Delta T$.

Students compare their measured chemical power against the theoretical power computed from the fuel's **lower heating value (LHV)** — 26.8 MJ/kg for ethanol, 50.0 MJ/kg for methane — and report the **combustion efficiency** as the ratio of measured to theoretical.

The result feeds the Reactivity Rocket Project's stoichiometric check: does the measured energy density support the project's design ethanol flow of 0.5 g/min, or do we need to specify a higher flow to deliver the engine's required thrust?

Introduction

Why this experiment matters

Engineering context

Every liquid-fuelled rocket engine designed since the V-2 has been defined by two numbers: the mass of fuel it burns per second, and the energy released per kilogram of fuel. The first sets the propellant budget. The second sets the thrust available.

This lab measures the second number — the **energy density** — directly, for the same fuels that are candidates for the project's copper engine. The Computational Engineering team uses your measured value (not the literature value) in their prediction sheet for the vendor burn.

Background — the chemistry

Ethanol combustion in oxygen:

$$\mathrm{C_2H_5OH_{(l)}} + 3\ \mathrm{O_{2\,(g)}} \longrightarrow 2\ \mathrm{CO_{2\,(g)}} + 3\ \mathrm{H_2O_{(l)}}$$

(1)

Methane combustion in oxygen:

$$\mathrm{CH_{4\,(g)}} + 2\ \mathrm{O_{2\,(g)}} \longrightarrow \mathrm{CO_{2\,(g)}} + 2\ \mathrm{H_2O_{(l)}}$$

(2)

In an *ideal* combustion, all the energy stored in the chemical bonds of the fuel is released as heat. In a *real* combustion in air with a school-grade burner, several mechanisms reduce the effective heat transfer to the water:

- **Incomplete combustion.** Some fuel exits as CO or soot rather than $\mathrm{CO_2}$. Visible yellow flame indicates incomplete combustion.
- **Heat loss to surroundings.** The flame radiates and convects heat to room air, walls, and the underside of the beaker support (tripod, gauze).
- **Evaporation from the beaker.** Some water leaves as vapour, taking latent heat with it but not registering as a temperature rise.

Together these reduce the heat actually absorbed by the water to typically **30–60 %** of theoretical. This factor is called the **combustion efficiency** for our open-flame rig.

Theory — heat capacity and power

The heat absorbed by a mass m_w of water with specific heat capacity c_w when its temperature rises by ΔT is:

$$Q = m_w \cdot c_w \cdot \Delta T$$

(3)

The specific heat capacity of water is **4.18 J g ¹ K ¹** (often written as 4.18 kJ kg ¹ K ¹).

The mean chemical **power** delivered to the water during a run of duration Δt is:

$$P_{\text{water}} = \frac{Q}{\Delta t}$$

(4)

The **theoretical** chemical power released by burning the measured fuel mass:

$$P_{\text{theory}} = \frac{m_f \cdot \text{LHV}_f}{\Delta t}$$

(5)

where LHV_f is the fuel's lower heating value. The **combustion efficiency** is:

$$\eta = \frac{P_{\text{water}}}{P_{\text{theory}}} = \frac{m_w \cdot c_w \cdot \Delta T}{m_f \cdot \text{LHV}_f}$$

(6)

Hypothesis

Hypothesis 1. Burning a known mass of ethanol under a beaker of water will raise the water's temperature in proportion to the fuel mass consumed, with combustion efficiency in the range 30–60 % for a school-grade burner, because heat losses to the room and evaporation account for the missing 40–70 %.

Hypothesis 2. Methane combustion will deliver approximately **1.9×** the chemical power per gram of fuel compared with ethanol, because methane's LHV (50 MJ/kg) is 1.87× that of ethanol (26.8 MJ/kg).

Hypothesis 3. The combustion efficiency of methane on the same rig will be slightly higher than ethanol's, because the methane flame is hotter (~1950 °C adiabatic vs ~2090 °C — these are similar; the real difference is that methane runs cleaner with no liquid-phase incomplete-combustion soot).

Materials and equipment

Per group

- 1 × 250 mL aluminium or borosilicate beaker (or a small saucepan)
- 1 × tripod + gauze mat
- 1 × 200 mL graduated cylinder (to measure water)
- 1 × electronic balance (0.01 g resolution)
- 1 × stopwatch
- 1 × thermometer (0–100 °C) **or** K-type thermocouple with MAX31855 amplifier and Arduino logger
- 1 × **ethanol spirit burner** with wick (refillable type), pre-filled with 40 mL denatured ethanol
- 1 × **Bunsen burner** with rubber hose to natural-gas tap
- Goggles + lab coat
- Heat-resistant gloves
- Paper towels (clean-up only — keep away from open flames)

Class

- Eyewash and CO extinguisher within 3 m of each working rig
- Lab coat (compulsory)
- Risk assessment form (lodged with technician)
- Tap for water refills between runs
- Stand and clamp (to position thermocouple at fixed depth)

Safety

The risk assessment for this experiment is rated **Low Risk** by the laboratory technician. Standard Stage 5 calorimetry controls apply.

1. **Ethanol burner refilling.** Refill only with the burner cool and the flame extinguished. Cap promptly. Place 30 cm away from any other flame source.
2. **Hot water and hot beaker.** A 200 mL beaker heated by a Bunsen for 90 s reaches 60–80 °C. Use heat-resistant gloves when moving the beaker. Set it on a wooden bench mat to cool — never on a cold sink (risk of thermal shock crack).
3. **Methane leaks.** Check the Bunsen hose connection every lesson. If you smell gas with the tap closed, do not light anything; inform the teacher.
4. **Flames in the fume cupboard.** Run the Bunsen flame inside the fume cupboard with the sash at the viewing line. The ethanol spirit burner may be used at the bench.

Method

Variables

Type	Variable	How it is controlled or measured
Independent	Fuel: ethanol vs methane	Two complete runs, one per fuel
Independent (optional)	Fuel flow rate	For methane, vary Bunsen air-hole open / closed; observe flame colour
Dependent	Water temperature rise (ΔT)	Thermocouple or thermometer, $\pm$ 0.5 °C
Dependent	Fuel mass consumed (m_f)	Pre / post weighing of burner, $\pm$ 0.01 g
Controlled	Volume of water in beaker	200 mL each run, measured with cylinder
Controlled	Beaker height above flame	Adjust tripod so the flame tip just touches the beaker base
Controlled	Run duration	90 s per run, timed with stopwatch
Controlled	Same beaker, same gauze	Wipe soot off the base between runs
Controlled	Initial water temperature	Refresh with cold tap water between runs; target 20 $\pm$ 2 °C

Procedure — ethanol calorimetry

1. **Zero the balance.** Place on a level bench and tare with the spirit burner cap on. Record the balance reading; this is the *gross* mass.
2. **Weigh the burner.** Place the burner on the balance, cap removed, wick exposed. Record $m_{\text{burner},1}$ to two decimal places.
3. **Fill the beaker.** Measure exactly **200 mL** of cold tap water into the beaker.
4. **Measure water initial temperature.** Place the thermometer or thermocouple in the beaker, stir gently with the thermometer for 10 s, then record T_1 to one decimal place.
5. **Set up the rig.** Place the beaker on the gauze on the tripod. Place the spirit burner directly under the tripod. The flame tip should reach the beaker base when lit.
6. **Light the burner.** Use a long match. The flame should be steady, approximately 4–5 cm tall, mostly blue with a slight yellow tip.
7. **Start the stopwatch** the moment the flame contacts the beaker.
8. **Stir gently** with the thermometer during the run. Do **not** touch the beaker walls with the thermometer.

9. **Stop at 90 s.** Cover the burner flame with the cap to extinguish.
10. **Record final water temperature.** Continue stirring for 5 s, then record T_2.
11. **Re-weigh the burner.** Allow 60 s for the burner to cool. Replace the cap. Reweigh. Record $m_{\text{burner},2}$.
12. **Fuel mass consumed.** $m_f = m_{\text{burner},1} - m_{\text{burner},2}$.
13. **Reset.** Pour out warm water; refill with cold; wipe soot from beaker base with damp paper towel.
14. **Repeat** for three trials.

Procedure — methane calorimetry

The procedure is identical to the ethanol calorimetry **except** the fuel-mass measurement.

Methane comes from the gas tap as a gas, not from a weighable burner. There are two ways to estimate the methane mass consumed in a 90 s run:

- **Method A — gas-meter reading.** If the lab has a gas meter on the tap, record the cubic-metre reading before and after the run; convert to mass using the natural-gas density (0.717 g/L at STP). This is the most direct method but few school labs have a meter.
- **Method B — literature flow rate.** A standard Bunsen burner at the typical lab supply pressure delivers approximately 0.5 L/min of natural gas. Use this as a calibration constant. Mass consumed in 90 s $\quad (0.5 \,/\, 60) \times 90 \times 0.717 = \mathbf{0.54\ g}$.

Use Method B unless your lab has a gas meter. Note the assumption in your report.

The water temperature measurement is exactly as for ethanol.

Risk assessment

A formal risk assessment for both rigs was prepared by the Laboratory Technician on 12 May 2026 in accordance with ISO 31000:2018. Both rigs are classified as **low risk** and authorised under routine classroom procedures. The signed assessment is on file with the laboratory.

Results

Raw data — ethanol calorimetry

Table 2: **Table 1.** Ethanol calorimetry raw data. Three trials per fuel, 200 mL water, 90 s burn.

Trial	$m_{\text{burner},1}$ (g)	$m_{\text{burner},2}$ (g)	m_f (g)	T_1 (°C)	T_2 (°C)	ΔT (°C)
1						
2						
3						
Mean						

Raw data — methane calorimetry

Table 3: **Table 2.** Methane calorimetry raw data.

Trial	Method (A or B)	m_f (g)	T_1 (°C)	T_2 (°C)	ΔT (°C)
1					
2					
3					
Mean					

Computed results

Table 4: **Table 3.** Calorimetric results. $m_w = 200$ g; $c_w = 4.18$ J g^{-1} K^{-1}.

Quantity	Ethanol	Methane
Mean fuel mass per run, m_f (g)		
Mean water temperature rise, ΔT (°C)		
Heat absorbed by water, $Q = m_w c_w \Delta T$ (J)		
Run duration, Δt (s)	90	90
Measured power to water, $P_w = Q/\Delta t$ (W)		
Theoretical fuel power, $P_{\text{theory}} = m_f \cdot \text{LHV}/\Delta t$ (W)		

Quantity	Ethanol	Methane
Combustion efficiency, $\eta = P_w/P_{\text{theory}}$		
Energy per gram of fuel measured (J/g)		
Energy per gram of fuel literature (J/g)	26 800	50 000

Worked example

Demonstration ethanol trial (made-up but realistic numbers).

Before: $m_{\text{burner},1} = 142.36$ g. After 90 s burn: $m_{\text{burner},2} = 141.62$ g.

$$m_f = 142.36 - 141.62 = 0.74 \text{ g of ethanol consumed} \tag{7}$$

Water: 200 mL = 200 g, with $T_1 = 21.0$ °C and $T_2 = 33.5$ °C, so $\Delta T = 12.5$ °C.

$$Q = 200 \cdot 4.18 \cdot 12.5 = 10\,450 \text{ J} \tag{8}$$

$$P_w = \frac{10\,450 \text{ J}}{90 \text{ s}} = 116 \text{ W} \tag{9}$$

Theoretical power from 0.74 g of ethanol with LHV = 26.8 MJ/kg over 90 s:

$$P_{\text{theory}} = \frac{0.74 \times 10^{-3} \text{ kg} \times 26.8 \times 10^{6} \text{ J/kg}}{90 \text{ s}} = 220 \text{ W} \tag{10}$$

Combustion efficiency:

$$\eta = \frac{116}{220} = 0.53 = 53\% \tag{11}$$

A 53 % efficiency is in the middle of the expected 30–60 % range for an open-flame ethanol calorimeter — consistent with significant heat loss to the room.

Observations

Record qualitative observations during each run.

Ethanol flame. *Colour? Steady or flickering? Did you see yellow soot tips? How far above the wick did the flame extend?*

Bunsen flame. *With air hole closed (yellow / luminous): describe the flame shape and the colour of the wick of the gauze afterwards. With air hole open (blue / non-luminous): same observations.*

Beaker base after each run. *Soot deposit? More for ethanol or methane? More for the closed-air-hole Bunsen or the open?*

Water during heating. *Did you see bubbles forming at any point? Where? Did steam visibly rise from the surface?*

Analysis

Comparison with literature LHV

Decision rule

For an open-flame school calorimeter, expect:

- Ethanol: combustion efficiency **30–60 %**; measured energy per gram approximately **8 000–16 000 J/g** (compared with literature 26 800 J/g).
- Methane: combustion efficiency **35–65 %**; measured energy per gram approximately **17 500–32 500 J/g** (compared with literature 50 000 J/g).

Your numbers should fall in these ranges. If they don't:

- Efficiency much **lower** (< 25 %) $\rightarrow$ probable issues are very yellow / sooty flame, beaker too high above flame, or wind / draughts cooling the beaker.
- Efficiency much **higher** (> 70 %) $\rightarrow$ probable issues are pre-heating of the beaker, mis-measured fuel mass (cap left off between weighings is a common error — ethanol evaporates).

Comparing ethanol and methane on the same rig

Use the same beaker, same water volume, same height, same duration. The ratio of measured powers should be approximately:

$$\frac{P_{w,\text{methane}}}{P_{w,\text{ethanol}}} \approx \frac{(m_f \times \text{LHV})_{\text{methane}}}{(m_f \times \text{LHV})_{\text{ethanol}}}$$

(12)

For 0.5 g ethanol vs 0.5 g methane this gives 1.87. For your actual measured fuel masses the ratio will differ.

Feeding the rocket project

What the Computational Engineering team does with your number

The rocket project's prediction sheet uses the *measured* energy per gram of fuel (not the literature value) to compute the predicted thrust at the vendor's design flow rate. Specifically, the predicted chemical power at 0.5 g/min ethanol flow is:

$$P_{\text{vendor, predicted}} = \frac{0.5 \text{ g/min}}{60 \text{ s/min}} \times (\text{your measured J/g ethanol})$$

(13)

For the demonstration trial above (14 100 J/g measured), this gives **117 W of chemical power at the vendor's design point** — a useful sanity-check number to put in the prediction sheet.

The combustion efficiency you measure is the **lower bound** for the vendor's pressurised burn. The vendor's chamber pressure raises the adiabatic flame temperature, reducing the fraction of incomplete- combustion CO; their measured efficiency will likely be 75–90 %.

Discussion

Did the data support the hypotheses?

For each hypothesis, follow the **Claim → Evidence → Reasoning** model.

Hypothesis 1 (ethanol combustion efficiency in the 30–60 % range). Quote your measured ethanol efficiency. State whether it fell in the expected band and identify the dominant heat-loss mechanism you observed.

Hypothesis 2 (methane delivers ~1.87× the power per gram of ethanol). Quote your measured ratio. Compare to the LHV-based prediction. Account for any significant difference using your observed combustion efficiencies for the two fuels.

Hypothesis 3 (methane runs cleaner than ethanol). Compare the soot deposit on the beaker base after each fuel. State which gave the higher combustion efficiency. Was the difference detectable in the data, given the precision of the thermometer?

Sources of uncertainty

Thermometer / thermocouple resolution

A standard lab thermometer reads to ± 0.5 °C. A K-type TC reads to ± 1 °C unless cold-junction-corrected. For a ΔT of about 12 °C, this gives a relative uncertainty of 4–8 % in the measured power.

Fuel mass measurement (ethanol)

The largest single error. The burner must be capped *every time it is weighed* — uncapped, ethanol evaporates at roughly 0.01 g/min, which over a 2 min weighing cycle can introduce a 0.02 g mass-loss artefact on top of the real 0.7 g consumption. Always cap before weighing.

Fuel mass measurement (methane)

We *assumed* a literature flow rate of 0.5 L/min at the tap, then multiplied by gas density to get mass. This is an indirect estimate with about ± 30 % uncertainty unless your school has a gas meter to confirm. The ethanol numbers are more trustworthy.

Heat loss to surroundings

The single biggest physical effect reducing efficiency below 100 %. Insulating the beaker (foil wrap, lid) increases efficiency by 5–15 % but doesn't eliminate the loss. The flame radiates and convects heat sideways to the room. This is a real limitation of open-flame calorimetry — vacuum-bomb calorimeters get to 95 %+ but aren't school equipment.

Comparison with the rocket project

This experiment's data feeds the rocket project in two ways.

1. Your **measured energy per gram of ethanol** parameterises the vendor-side thrust prediction. The Computational Engineering team's Rust function `predict_vendor_burn` consumes this number.
2. Your **combustion-efficiency factor** is the basis for the Heat Exchanger team's reconciliation expectation: the vendor's measured chamber wall temperature will exceed your prediction by roughly $(1-\eta_{\text{school}})/(1-\eta_{\text{vendor}})$ because their pressurised combustion runs cleaner.

Conclusion

State your conclusion in four sentences.

1. Quote the chemical-power-to-water delivered by your ethanol and methane rigs.
2. Quote the corresponding combustion efficiencies and state whether they fell in the expected 30–60 % / 35–65 % bands.
3. State whether your ethanol-vs-methane power ratio matched the LHV-based prediction of ~1.87×, and explain any residual.
4. Suggest one specific improvement that would raise the combustion efficiency by at least 10 percentage points without changing the fuels.

Extension questions

Q1. A vendor reports that their pressurised ethanol-O burn at 0.5 g/min ethanol delivers 220 W of chemical power. Using your measured combustion efficiency, predict whether the vendor's claim is consistent with the chemistry at that flow rate. Show working.

Q2. Repeat the ethanol calorimetry with the beaker wrapped in aluminium foil except for the bottom (foil "skirt" extending below the beaker rim). Predict the change in combustion efficiency, then test.

Q3. Methane and propane (LPG) have similar adiabatic flame temperatures and very similar combustion chemistry. Propane LHV is 46.4 MJ/kg vs methane 50.0 MJ/kg. Predict the ratio of measured-power-to-water for propane vs methane on the same rig.

Q4. A "rich" Bunsen flame (air hole closed, yellow / luminous) deposits significant soot on the beaker. Soot has a thermal conductivity 100× lower than aluminium. Predict and explain how this affects the measured power-to-water on subsequent runs.

Q5. Sketch a labelled energy-flow diagram for the calorimeter: chemical energy in fuel → heat released by combustion → heat absorbed by water + heat lost to air + heat lost via evaporation + heat absorbed by beaker. Estimate the fraction of total chemical energy ending up in each pathway, given your measured 53 % efficiency.

References

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