McGill International Physicists' Tournament

Problem #4: Travelling Flames

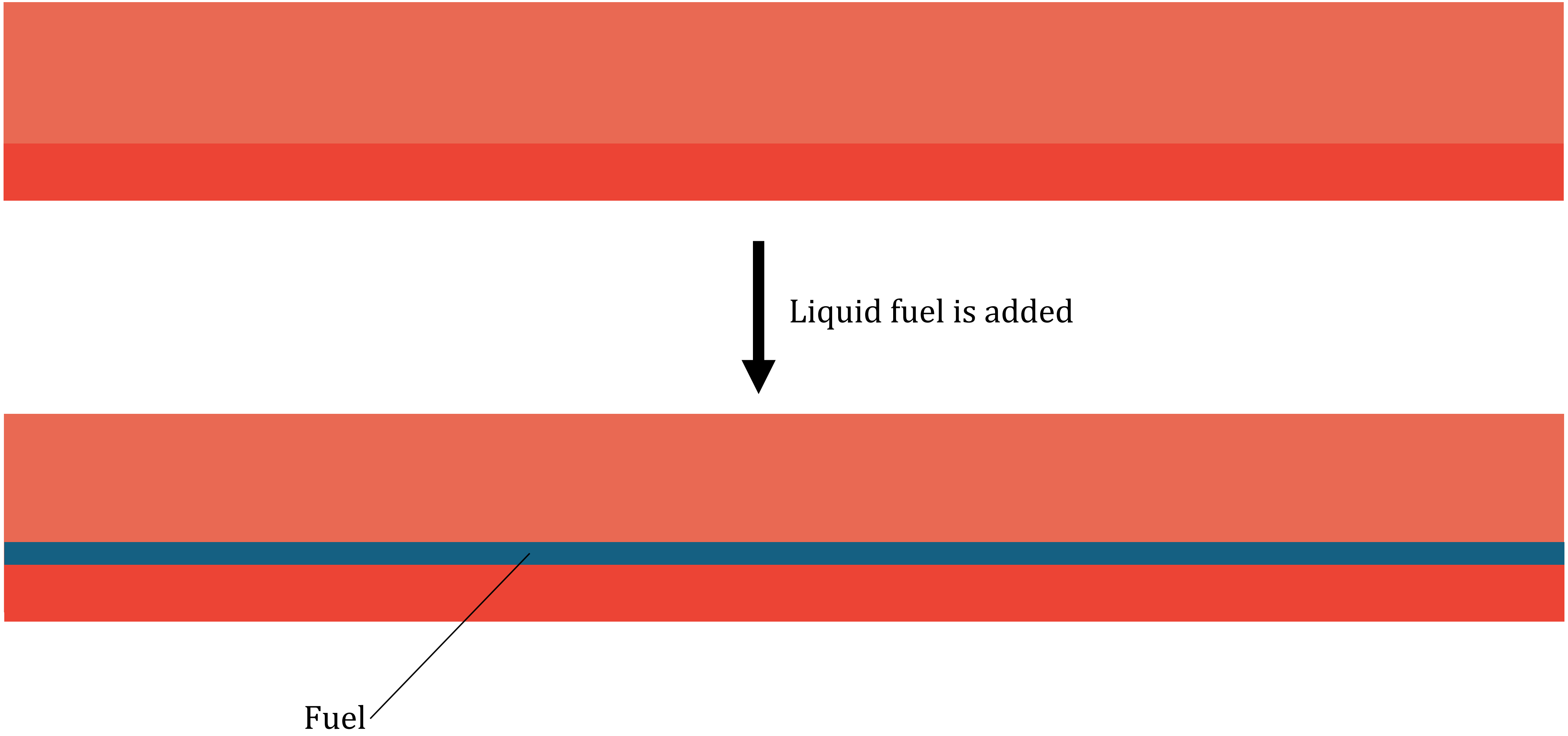
Problem Statement

Under certain circumstances a flame can travel along an open canal.

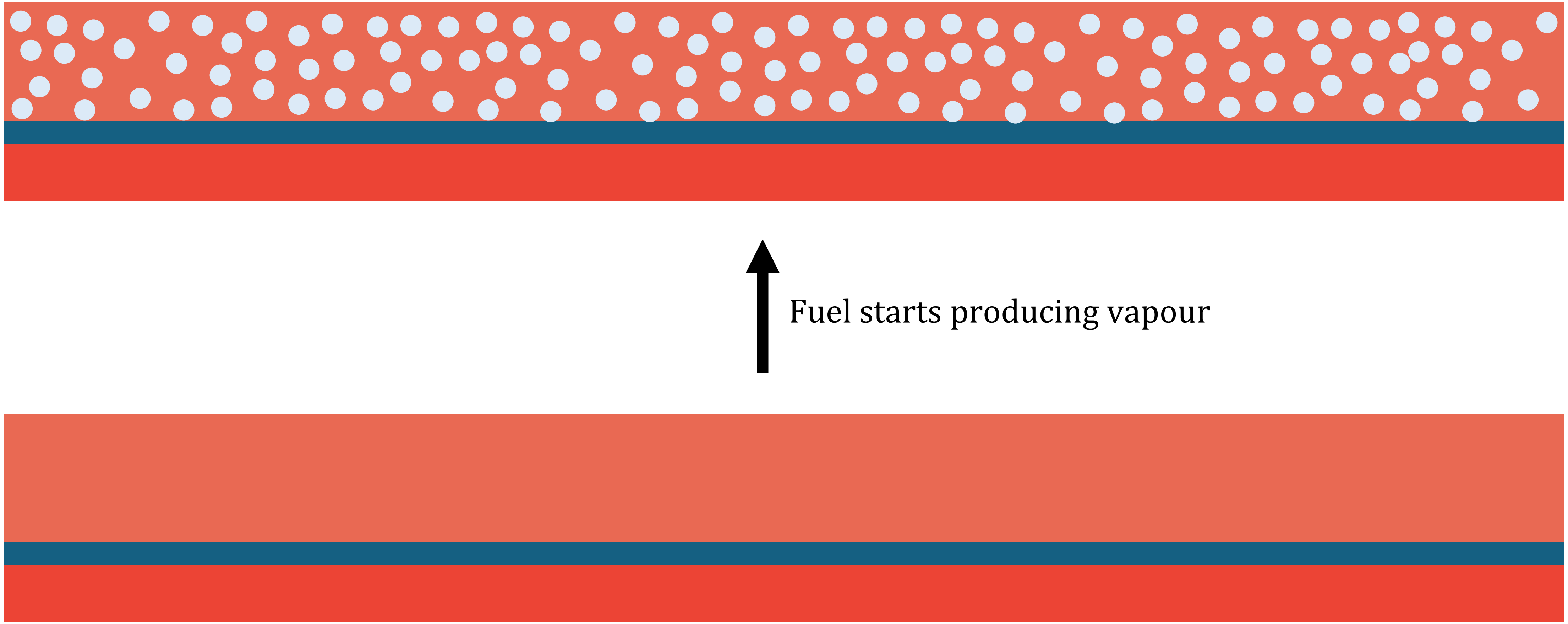
- Explain the **phenomenon**.
- Investigate its **lifetime** and **speed**.
- Under which **circumstances** does it display a **periodic behavior**?
- Maximize the **lifetime** of a traveling flame for a given amount of fuel.

The Phenomenon - Explanation

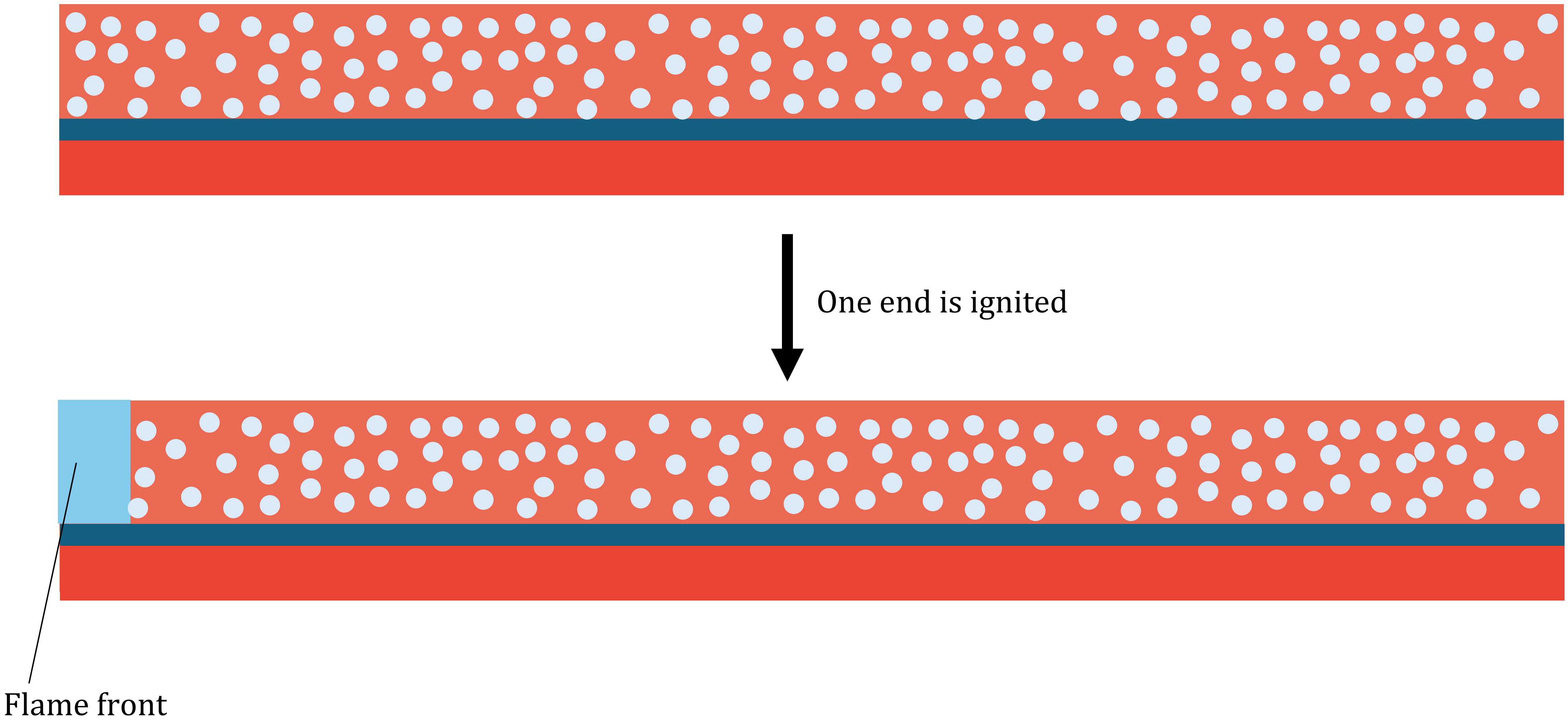
Side view of a straight track



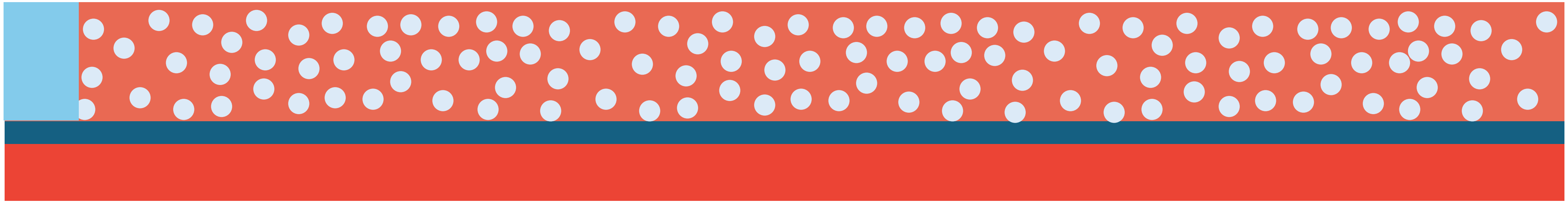
The Phenomenon - Explanation



The Phenomenon - Explanation

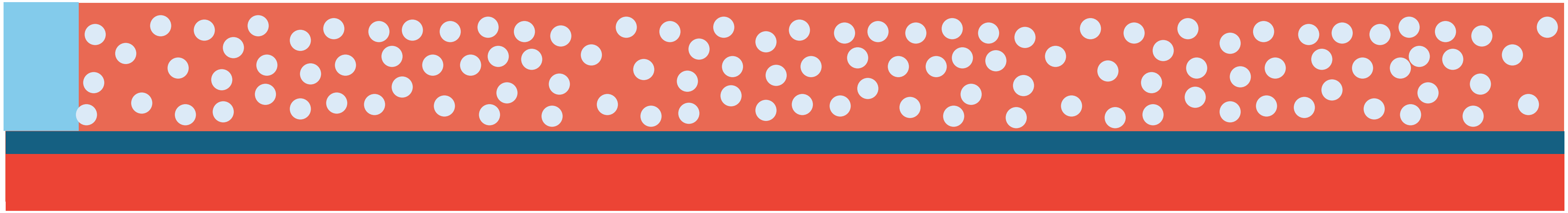


The Phenomenon - Explanation

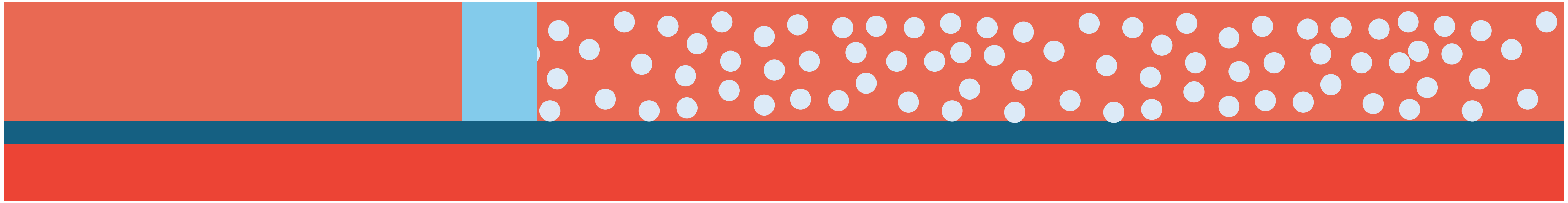


The flame starts travelling along the track

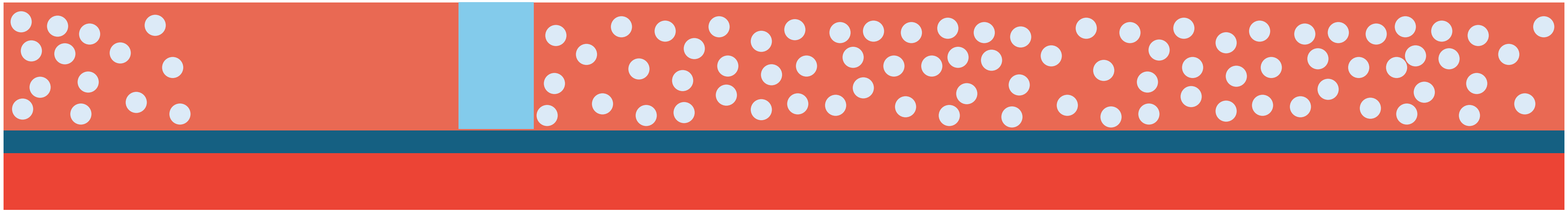
At the same time, the vapour at the original ignition point is entirely consumed and the flame at that specific point dies out



The Phenomenon - Explanation



As the flame travels, vapour at the beginning of the track starts to replenish

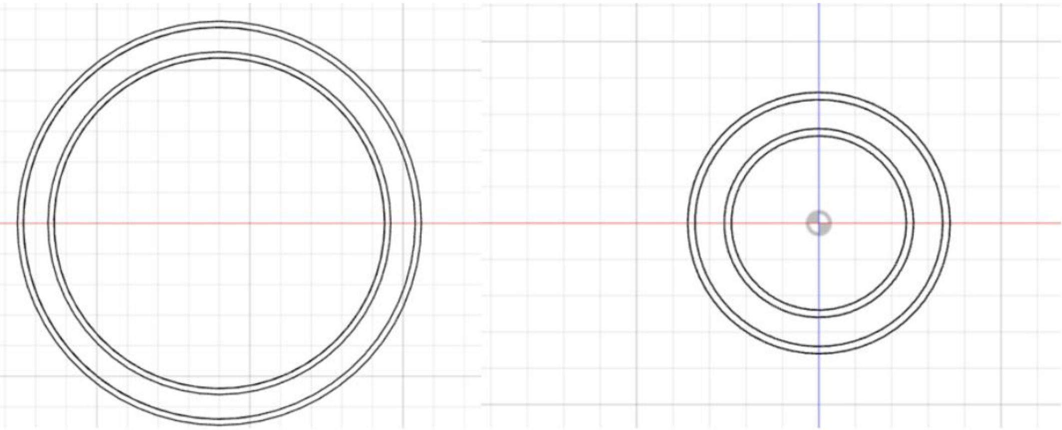


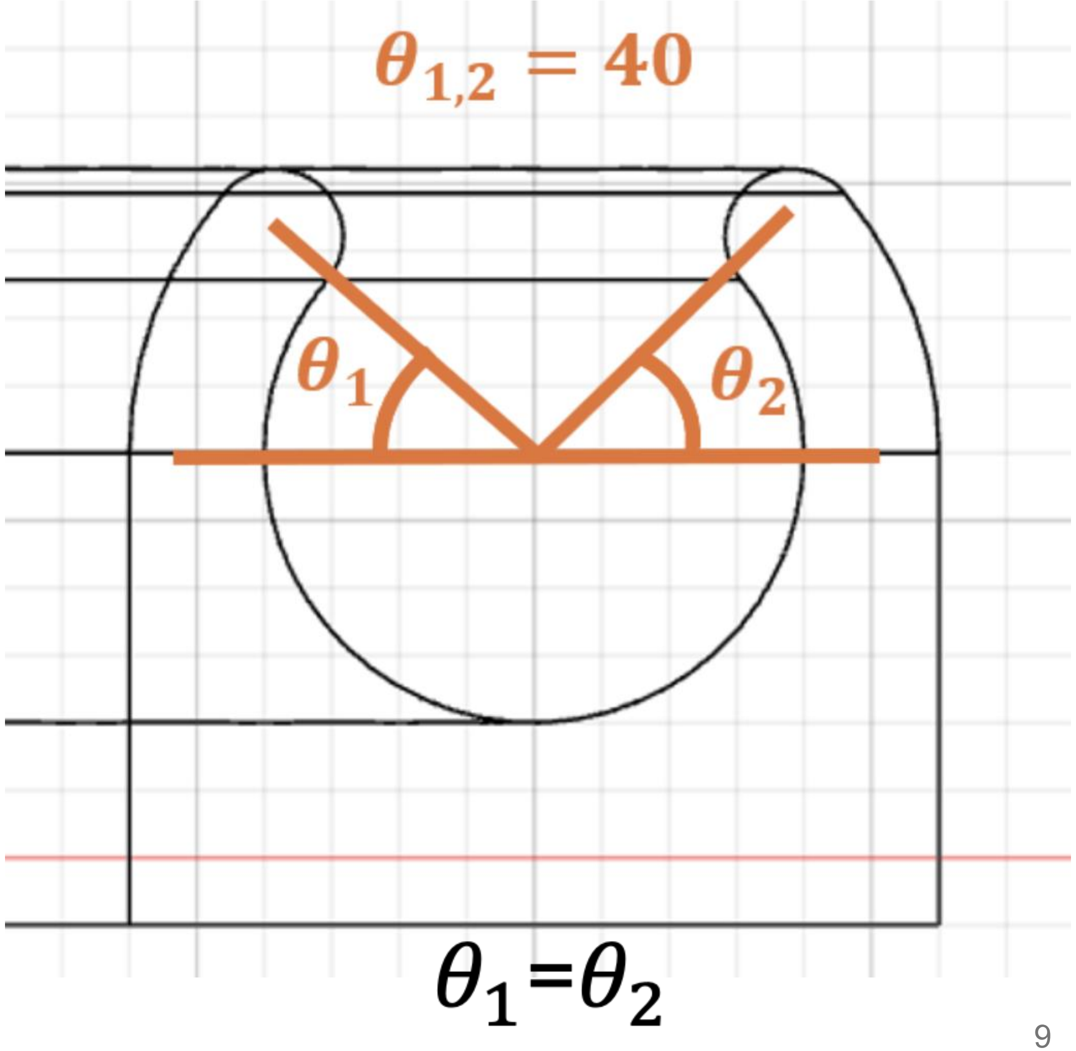
However, on a circular track

The Phenomenon - Explanation

However, on a circular track

3D Printed Channels





Theoretical Model

Laminar flame velocity (S_L)

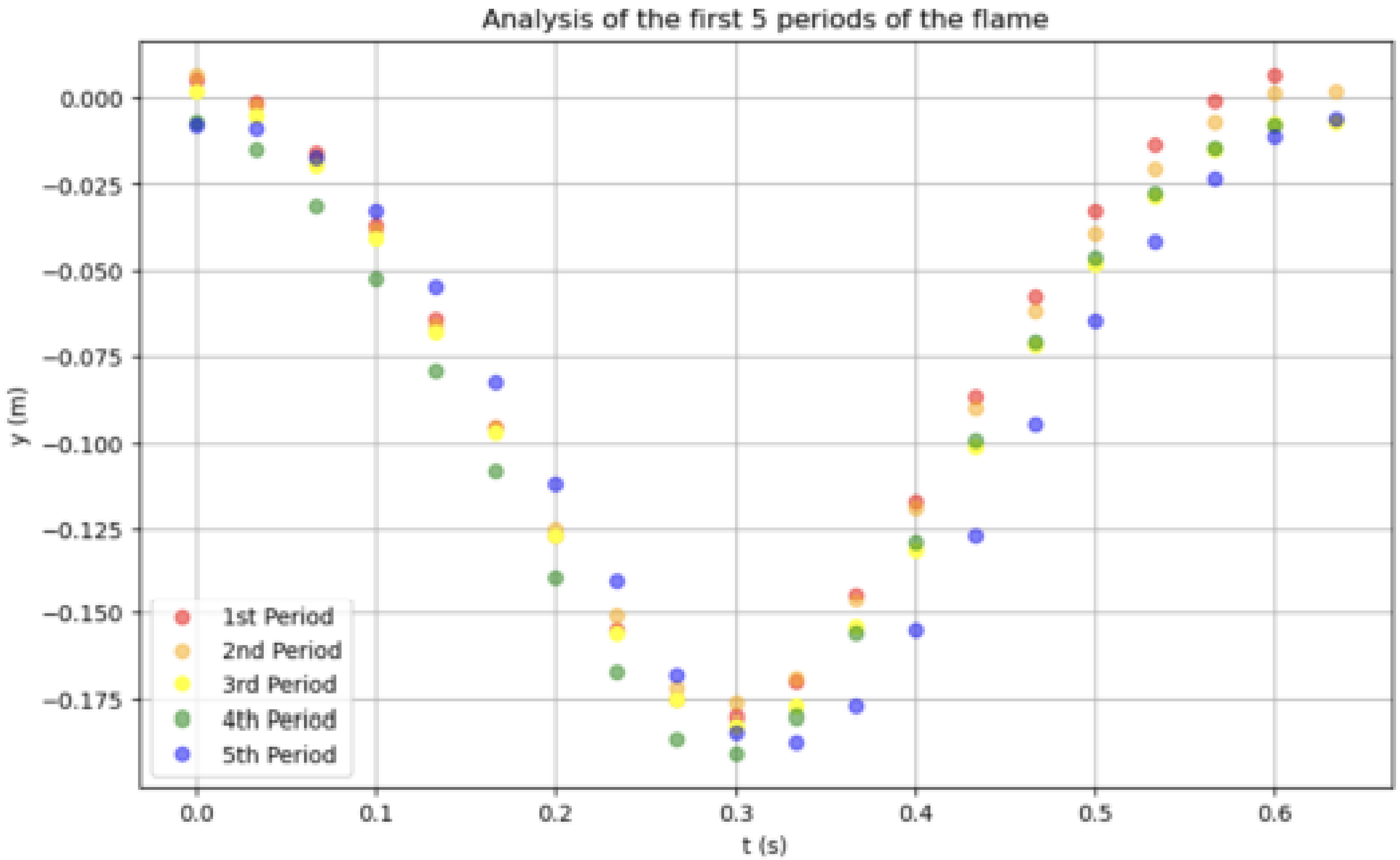
$$S_L = \sqrt{\alpha\dot{\omega}\frac{T_B - T_i}{T_i - T_u}}$$

↓

$$\dot{\omega} = Ae^{\frac{-E_a}{k_b T}}[F]^n[O]^m$$

α = Thermal diffusion constant
$\dot{\omega}$ = Reaction rate
T_B= Burnt fuel temperature
T_i= Ignited fuel temperature
T_u = Unburnt fuel temperature

A = Pre-exponential factor
E_a= Activation Energy
k_b=Boltzmann Constant
$[F]$= concentration of fuel
$[O]$= Concentration of oxidizer
n, m= partial orders from empirical formula



Flame undergoes no significant acceleration over time

Theoretical Model

Lifetime of the Flame

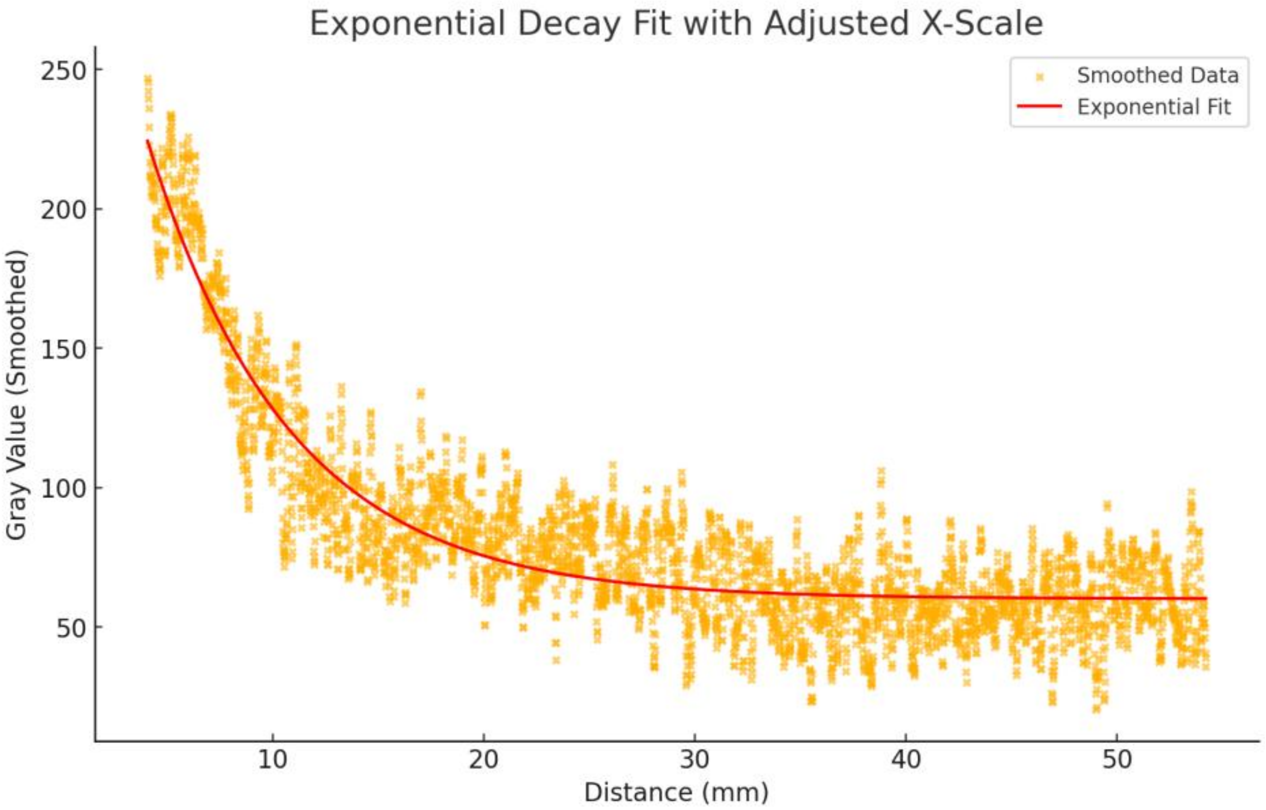
$$M(T) = T(298) \cdot \sigma(T) \cdot t \cdot A$$

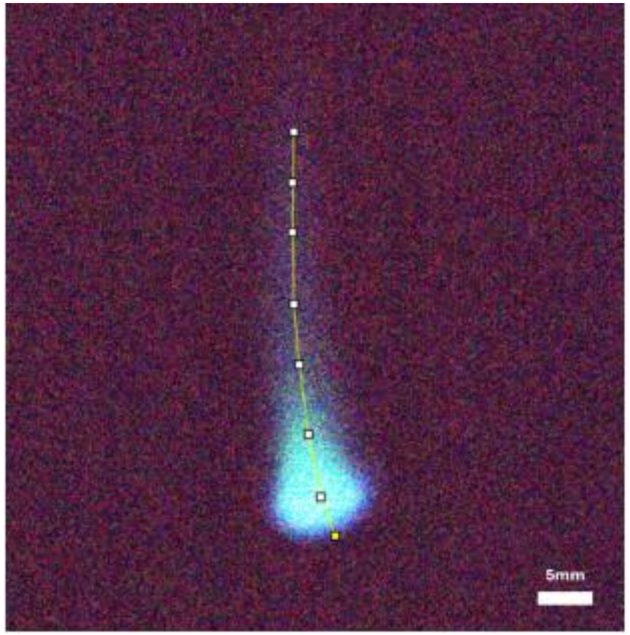
↓

$$T(x) = T_b e^{-\gamma x} + T_0$$

t = time
A = Surface area of the opening of the channel
$T(x)$ = Temperature of the fuel across the channel
γ = decay rate of the flame
T_0 = minimum temperature of the channel
T_b = Temperature of the flame

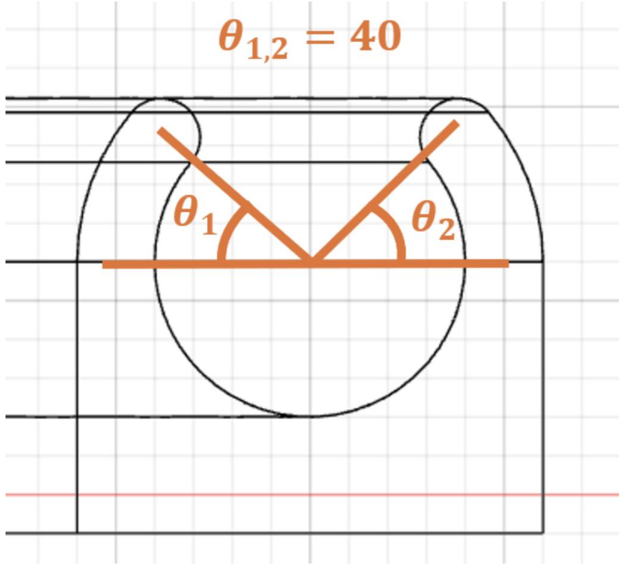
Results : Brightness vs Temperature

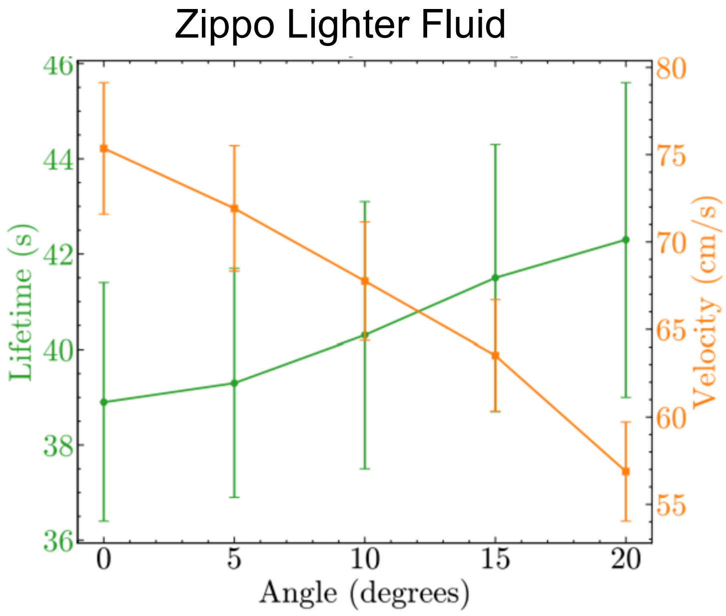


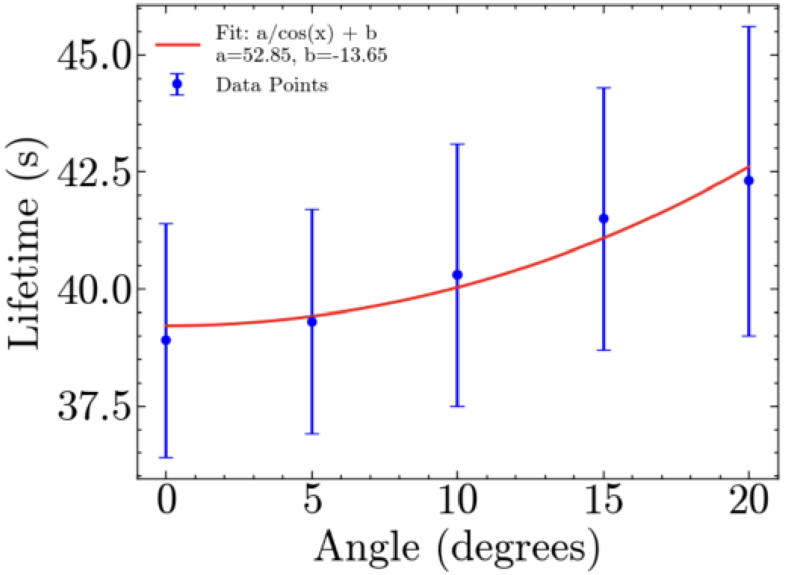


$$I \propto \sigma T^4$$

Results : Varying Angle of Opening

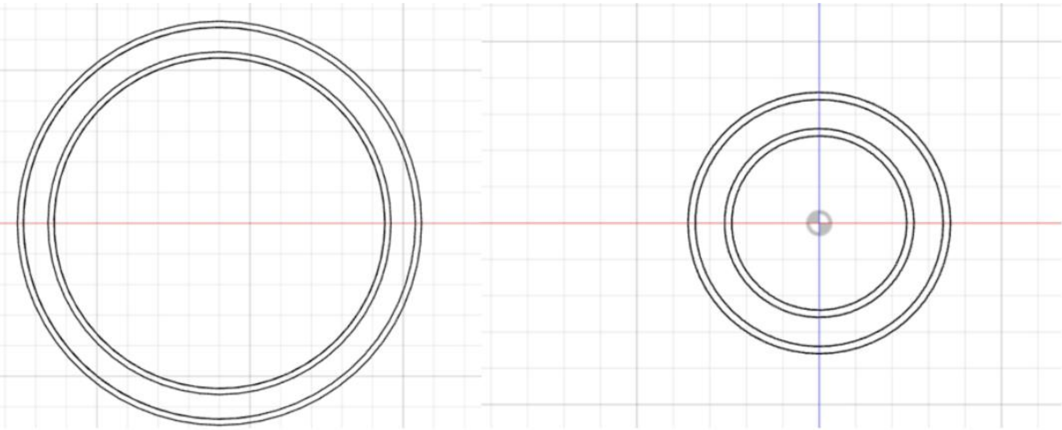




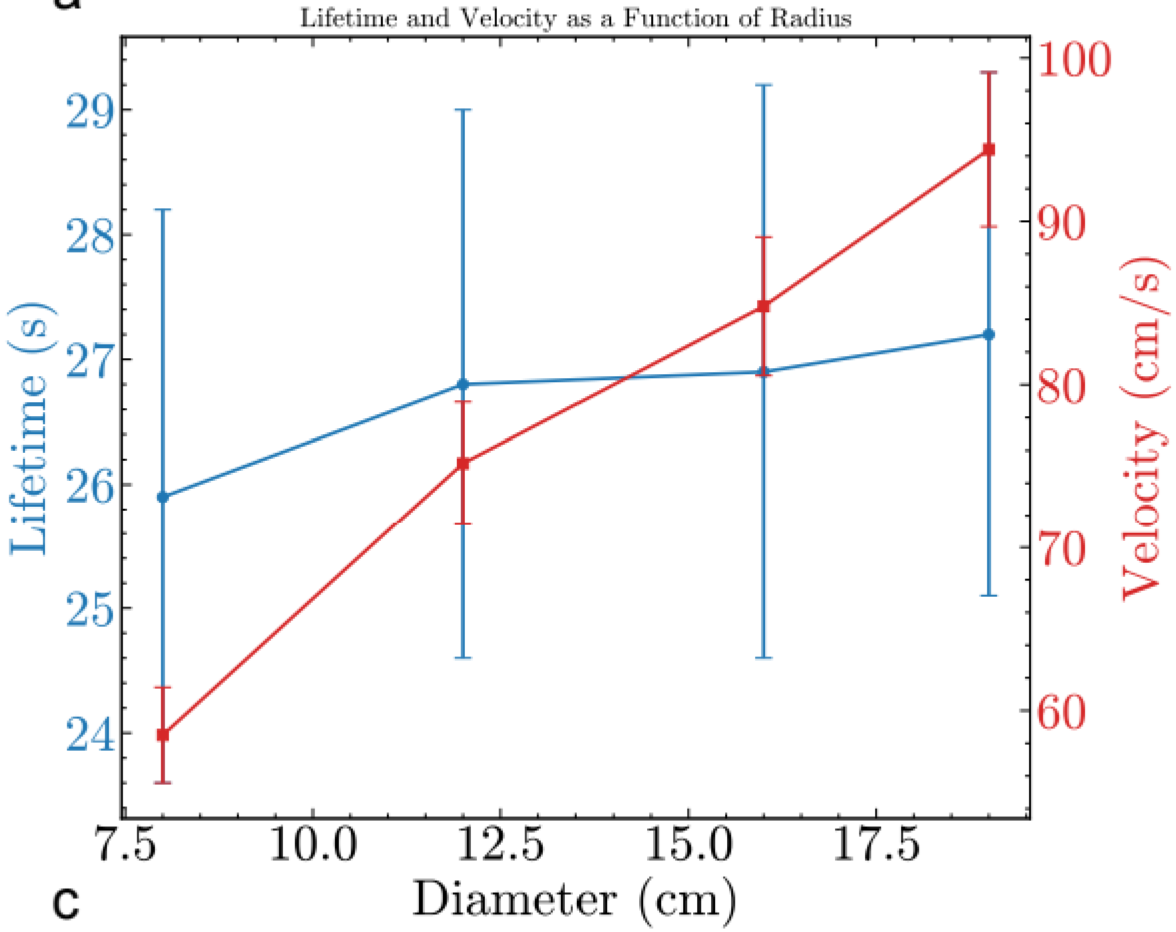


- Lifetime increases as the opening increases
- Less air → less combustion → lower burning temperature → lower reaction rate → longer lifetime
- Flame burns colder → flame cannot ignite the fuel as far → lower velocity

Results: Varying Size of the Ring



a

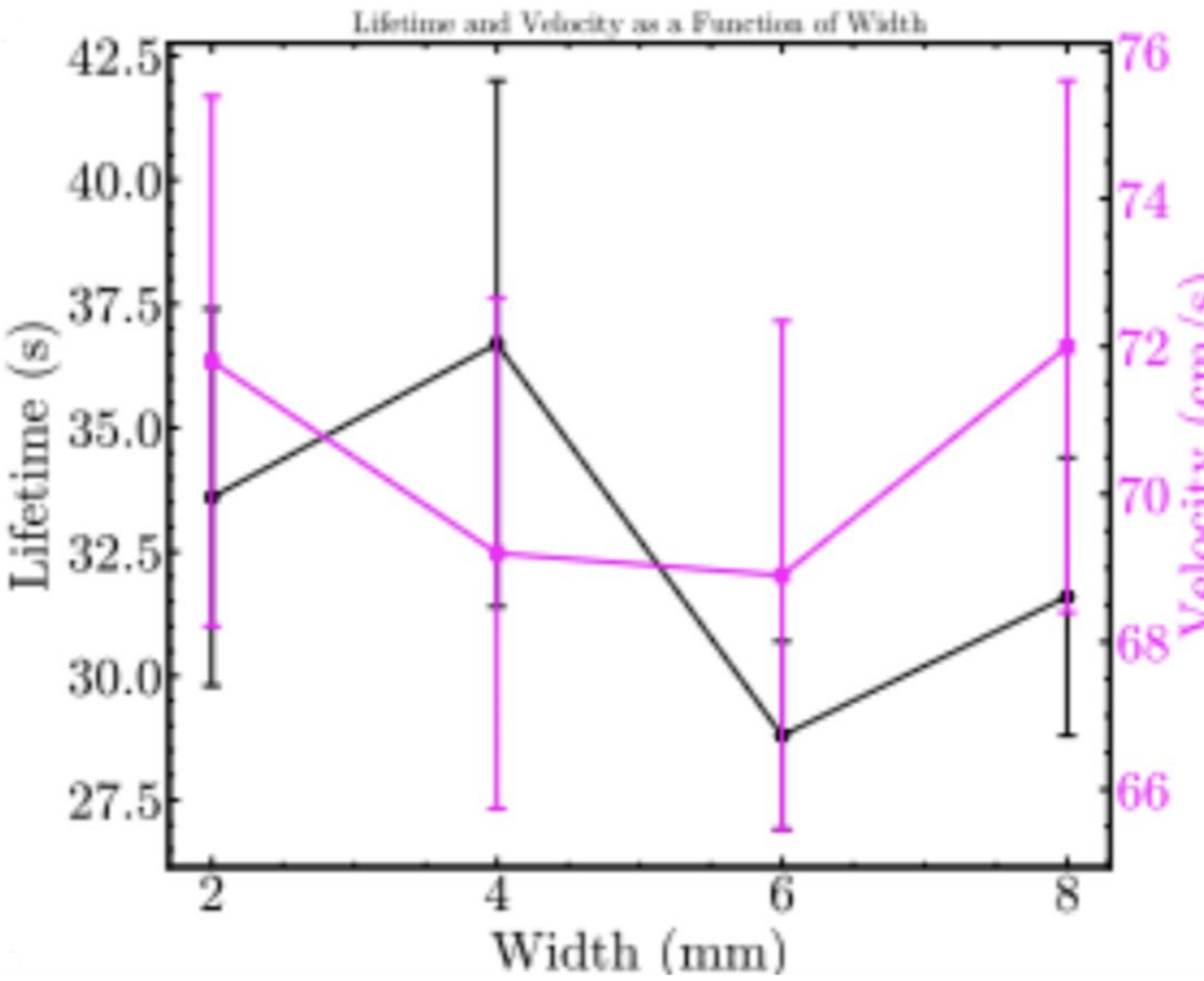


c

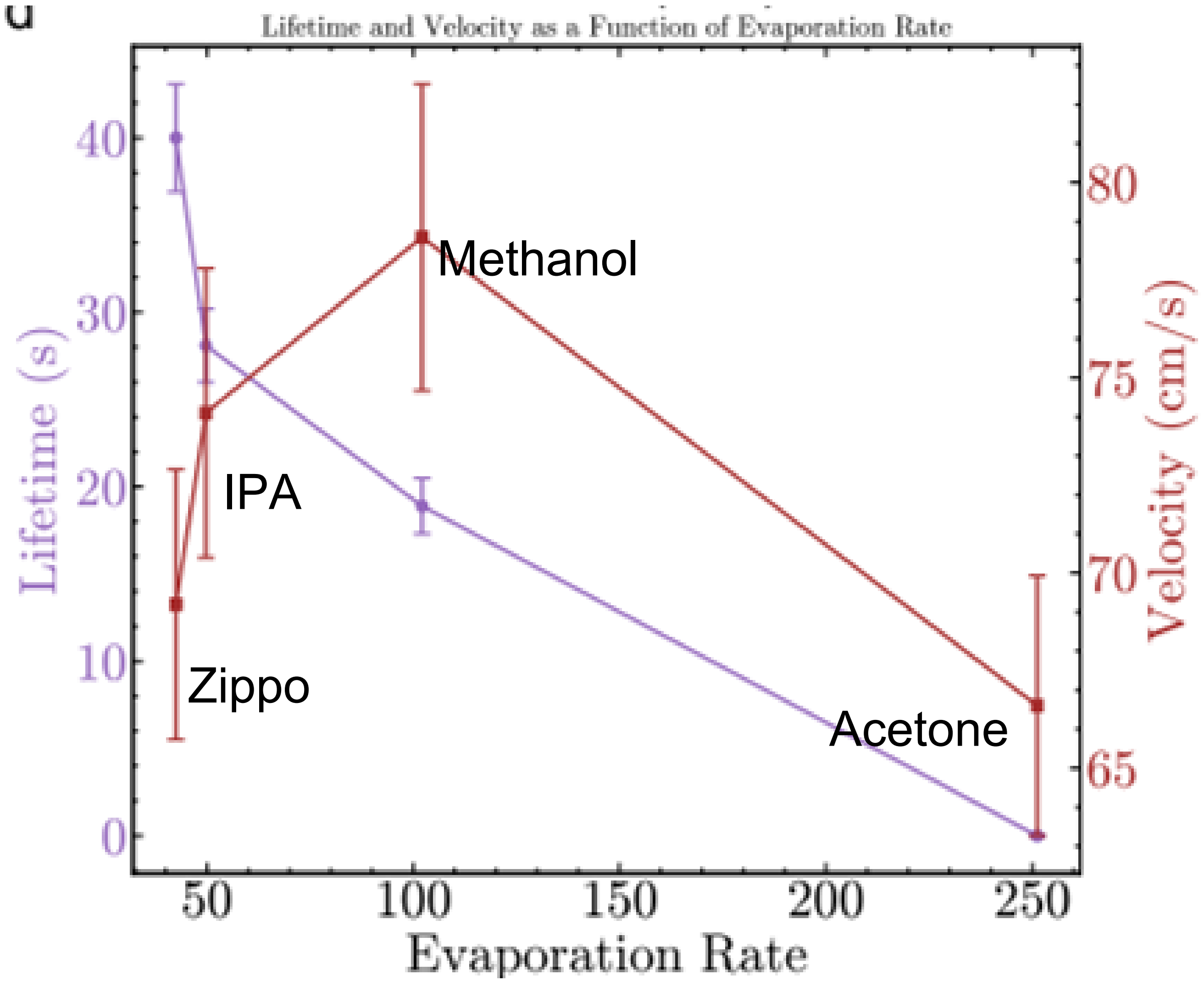
- Velocity increases with an increasing radius
- Longer radius → more time for air to diffuse into channel and more fuel to evaporate → larger reaction rate → more heat → molecules further away from flame front get ignited

Results: Varying Width of the Ring

- Lifetime and Velocity do not change in statistically significant way



Results: Varying Evaporation Rate



Results

Fuel	Theoretical Flame Velocity (cm/s)	Experimental Flame Velocity (cm/s)
Acetone	58.2	66.6
IPA	88.7	74.1
Methanol	97.6	78.6
Zippo Lighter Fluid	n/a	69.2

- Zippo Lighter fluid could not be estimated because not enough data available
- Although not correct, adds credibility to model because they are in correct order
- Can be used to estimate the evaporation rate of Zippo Lighter Fluid
- The fuels with the highest velocity had the lowest lifetime

Conclusions

Lifetime and Speed

Conclusions:

- Increasing opening
  - Lifetime increases
  - Speed decreases

- Increasing size
  - Lifetime increases
  - Speed increases

- Increasing the Width of the Ring
  - Lifetime and Speed have no effect
- Increasing Evaporation Rate
  - Lifetime decreases
  - Speed increases

Maximizing the lifetime

Conclusions:

- Minimize size of opening
  - minimizes evaporation rate of fuel

- Larger radii rings
  - decreases temperature of fuel → decreases evaporation rate

- Use fuels with lower evaporation rates: Zippo Lighter fluid

Materials

- Fuels:
    - Methyl-Acetate Water mixture
    - Methanol
    - Isopropyl Alcohol
    - Acetone
    - Zippo Lighter Fluid

- DSLR Camera
- 3D Printed Channel
- Syringe
- Lighter
- Temperature Meter and Thermocouple
- Phone camera

Equation for CDF of the Boltzmann distribution

$$\sigma(T) = \frac{1-\operatorname{erf}\left(\frac{v}{\sqrt{2}\left(\sqrt{k\cdot\frac{T(x)}{m}}\right)}\right)+\sqrt{\frac{2}{\pi}}\left(\frac{v}{\left(\sqrt{k\cdot\frac{T(x)}{m}}\right)}\right)\exp\left(-\frac{v^2}{2\left(\sqrt{k\cdot\frac{T(x)}{m}}\right)^2}\right)}{1-\left(\operatorname{erf}\left(\frac{v}{\sqrt{2}\left(\sqrt{k\cdot\frac{298}{m}}\right)}\right)-\sqrt{\frac{2}{\pi}}\left(\frac{v}{\sqrt{k\cdot\frac{298}{m}}}\right)\exp\left(-\frac{v^2}{2\left(\sqrt{k\cdot\frac{298}{m}}\right)^2}\right)\right)}$$

$v = velocity\ needed\ to\ overcome\ the\ enthalpy\ of\ evaporation\ of\ the\ fuel$

$k = Boltzmann\ constant$

$m = mass\ of\ molecule$

$T(x) = temperature\ of\ fuel\ across\ length\ of\ the\ channel$

Chemical Reactions for Combustion

Methanol: $2\,CH_3OH\,(g) + 3\,O_2(g) \longrightarrow 2\,CO_2\,(g) + 4\,H_2O\,(g)$

Acetone: $C_3H_6O\,(g) + 4\,O_2(g) \longrightarrow 3\,CO_2\,(g) + 3\,H_2O\,(g)$

Isopropyl Alcohol: $2\,C_3H_8O\,(g) + 9\,O_2(g) \longrightarrow 6\,CO_2\,(g) + 8\,H_2O\,(g)$