02 Plume of Smoke

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Team Germany

The Problem

If a burning candle is covered by a transparent glass, the flame extinguishes and a steady upward stream of smoke is produced. Investigate the plume of smoke at various magnifications.

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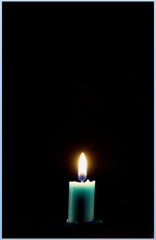

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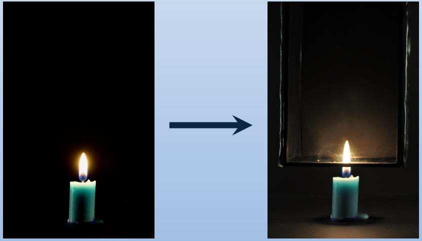

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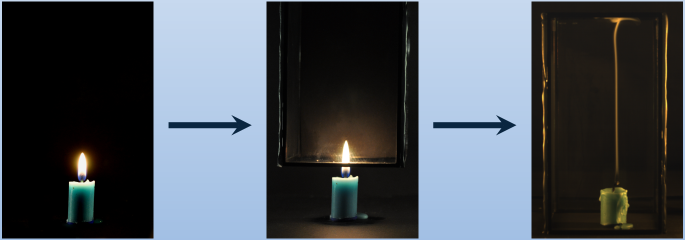

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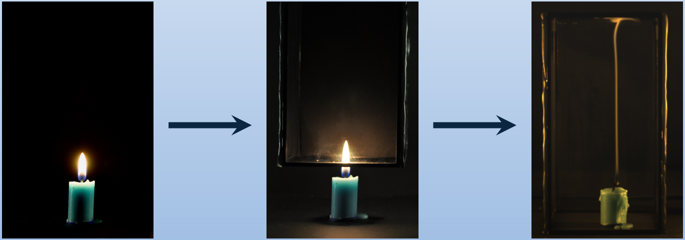

Phenomenon

Investigated Scales

Macroscopic Scale

- plume's basic physics
- influence of the glass

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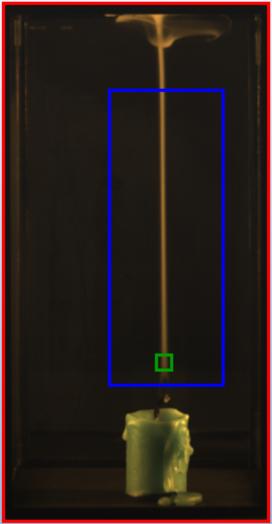
Mesoscopic Scale

- free flow of smoke
- laminar and turbulent motion

Investigated Scales



Macroscopic Scale

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Mesoscopic Scale

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Microscopic Scale

- motion of single particles
- optical phenomenons

The smoke

- Definition: Mixture of solid particles and fluid droplets in a gaseous phase mostly resulting from combustion reactions
- Smoke of a Candle:
    - complete combustion of paraffin:

      $$2\ C_nH_{2n+2} + (3n+1)\ O_2 \rightarrow 2n\ CO_2 + 2(n+1)\ H_2 0$$

    - incomplete combustion of paraffin - example:

      $$C_{20}H_{42} + 19O_2 \rightarrow 6CO_2 + 8CO + 4C + C_2H_6 + 18H_2O$$

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Macroscopic Scale

Basic Explanation

- smoke behaves similiar to air
- temperature gradient
- buoyancy

Influence of the glass

- deceleration of smoke due to temperature gradient
- shape of the smoke plume
- isolation from environment

Basic explanation

- Rising of smoke through driving pressure

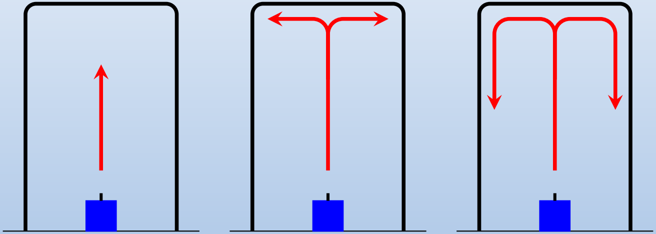
$$\Delta p = hg(\rho_2 - \rho_1)$$

- Dependence on local temperature

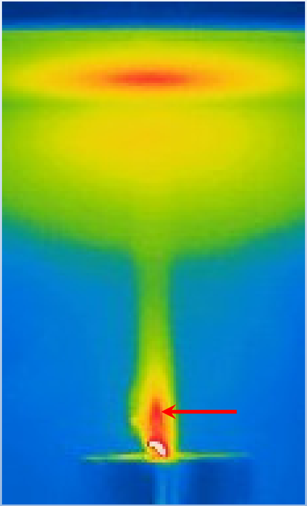
$$\rho \propto \frac{1}{T}$$

p: pressure
h: effective height
g: gravitational acceleration
ρ: density
T: temperature

Motion of smoke in the glass



Predictions on velocity

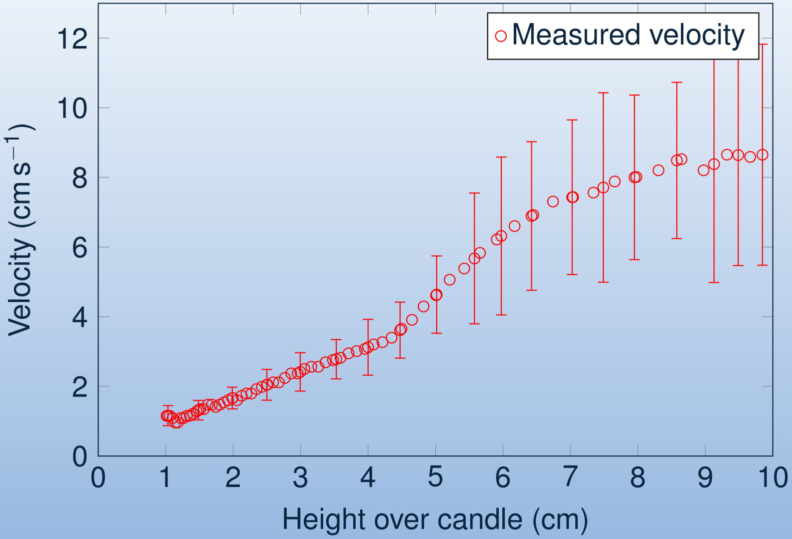


Deceleration through backed up air

Acceleration through temperature gradient

Slow through opposite temperature gradient

Measurement of velocity



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Characteristic numbers of flow

Reynolds number

$$Re = \frac{vd}{\nu}$$

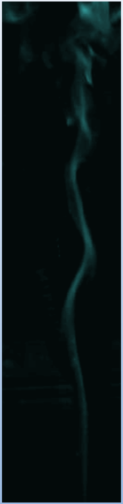
with v flow velocity, d characteristic length and ν kinematic viscosity

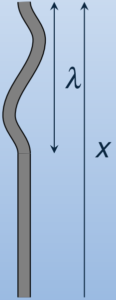
Prandtl number

$$Pr = \frac{\nu}{\lambda}$$

with ν kinematic viscosity and λ thermal conductivity

Fluid dynamics states





Turbulent flow ($Re > Re_{crit}$)

- irregular and chaotic
- strong diffusivity and dissipation

→ hardly describable

Transient flow ($Re \approx Re_{\text{crit}}$)

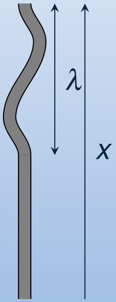
- Critical height x, wavelength λ
- x correlates to v_{crit}, depending on Q

Laminar flow ($Re < Re_{\text{crit}}$)

- Non diffusing velocity layers
- Gaussian velocity distribution profile

Correlation of transition with candle properties

"Mechanism for transition to turbulence in buoyant plume flow"
Shigeo Kimura and Adrian Bejan



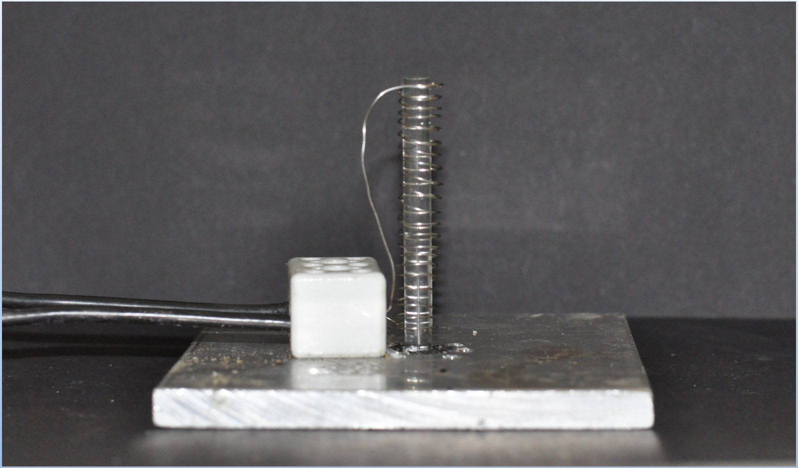
$$\frac{x}{x_0} = \left(\frac{Q}{Q_0}\right)^{-1/2}$$

$$\frac{\lambda}{\lambda_0} = \left(\frac{Q}{Q_0}\right)^{-1/2}$$

Assumptions:

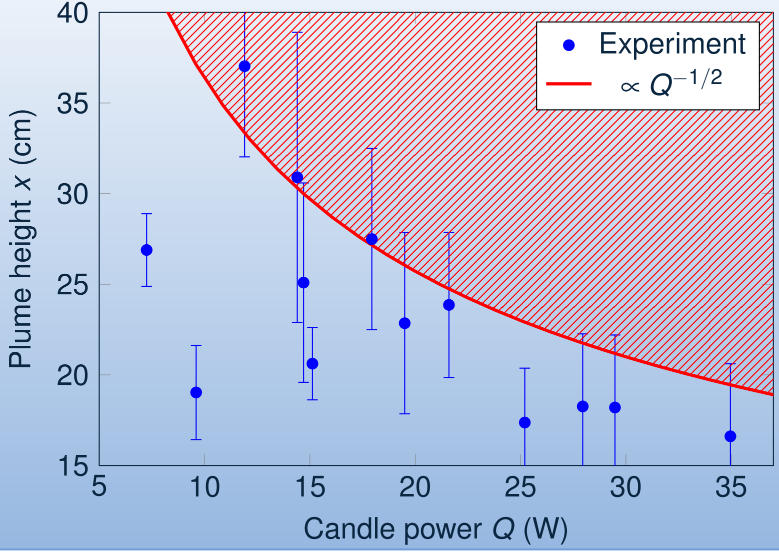
- closed box
- Prandtl number O(1)
- point heat source

Improved Assembly: Artifical Candle



Swaying motion

Measurement of transition height to candle power



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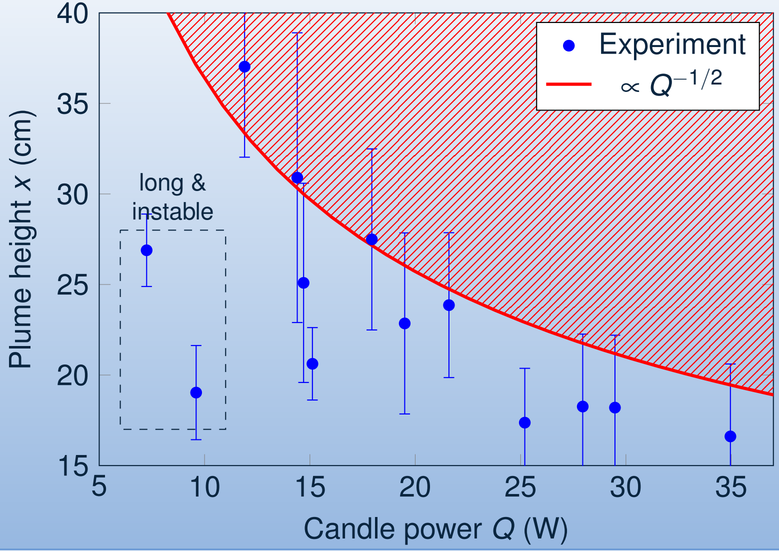
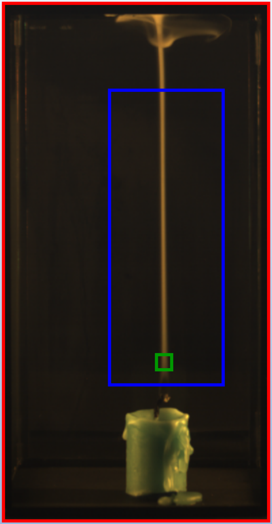


Investigated scales



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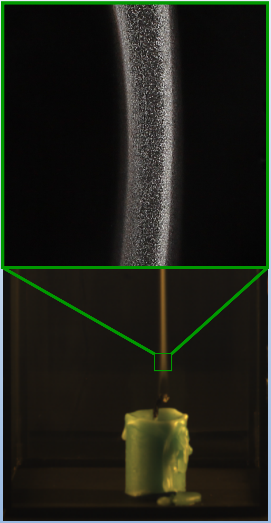
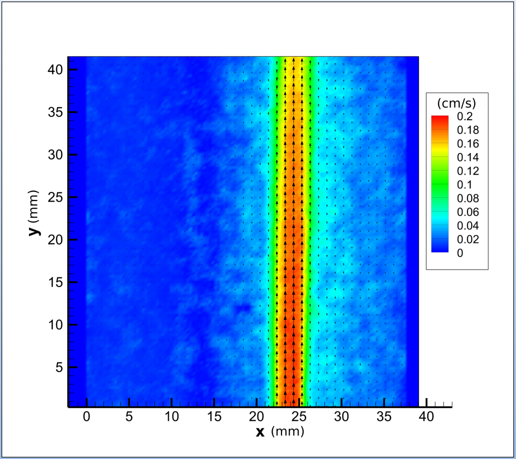
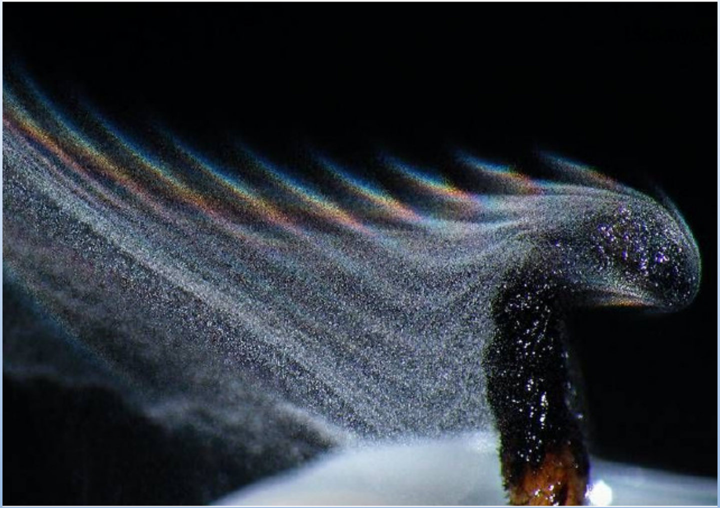


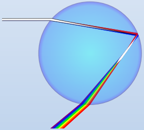
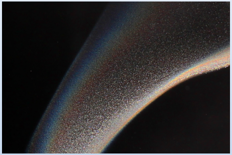
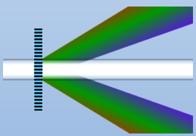
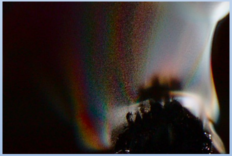
Velocity profile inside laminar stream



Optical Effect



Possible Explanation of Optical Effects

Explanation	Expectation	Observations
Refraction 	Rainbow-like • few angles • transmission required	
Diffraction 	Colored Interference • small particles • continuous pattern	

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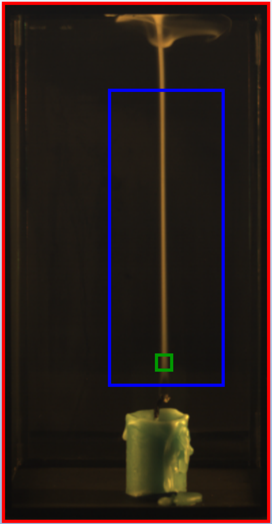

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Appendix

Relevant Parameters: Temperature

Influence of higher Temperature in the glass:

- Lower Velocity of rising plume of smoke due to lower temperature difference, so lower pressure difference
- Faster diffusion due to accelerated browne's molecular movement

Relevant Parameters: Shape of glass

Smoke follows shape of glass:

Heat input of the candle

Influence of higher heat input of the candle:

- lower transition height x:
  $\frac{x}{x_0} = \left(\frac{Q}{Q_0}\right)^{-\frac{1}{2}}$
- lower transition wavelength λ:
  $\frac{\lambda}{\lambda_0} = \left(\frac{Q}{Q_0}\right)^{-\frac{1}{2}}$

Characteristic numbers of flow: Reynolds number

- Ratio between inertia and friction force
- Defined as $Re = \frac{vd}{\nu} = \frac{\rho vd}{\eta}$

Characteristic numbers of flow: Rayleigh number

Characteristic numbers of flow: Grashof number

- Used to describe flow in thermal convection
- Defined as $Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$
  with g earth acceleration
  β volumetric expansion coefficient
  T_s temperature
  T_∞ rest temperature
  L characteristic length
  ν kinematic viscosity

Characteristic numbers of flow: Prandtl number

- Ratio between kinemeatic viscosity and thermal conductivity
  $Pr = \frac{\nu}{\beta}$
- Assumed as unity

Characteristic numbers of flow: Froude number

- Ratio of inertia forces to gravitational forces

$$Fr = \frac{v^2}{gL}$$

with v flow velocity, g earth acceleration, L characteristic length

The smoke

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- Smoke of a Candle:
  - complete combustion of paraffin:

    $$2\ C_nH_{2n+2} + (3n+1)\ O_2 \rightarrow 2n\ CO_2 + 2(n+1)\ H_20$$

  - incomplete combustion of paraffin - example:

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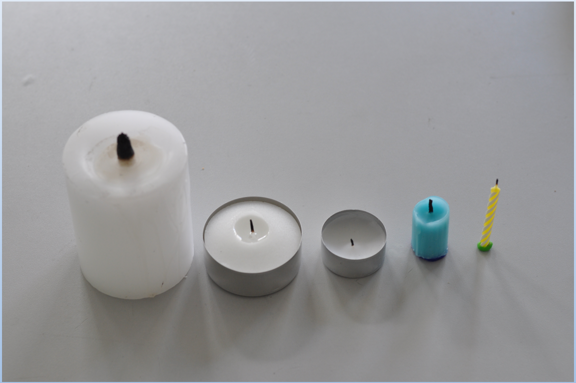
Quadratic rainbow

Different candles



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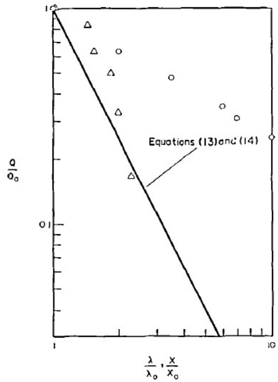


FIG. 3. The transition height and the wavelength as a function of heat input, in the absence of external noise. ○, x/x_0, transition height. △, λ/λ_0, wavelength.

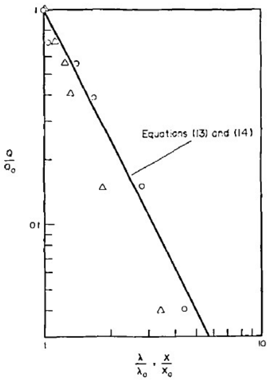
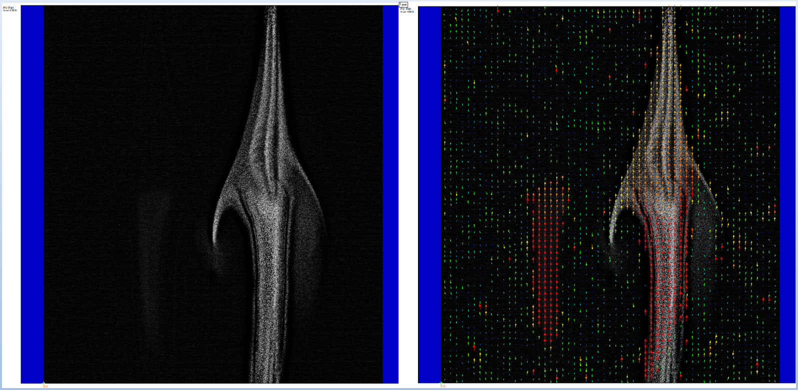


FIG. 4. The transition height and wavelength as a function of heat input. The enclosure wall was tapped by a finger. ○, x/x_0, transition height. △, λ/λ_0, wavelength. $Q_0 = 55$ W, $x_0 = 0.25$ m, $\lambda_0 = 0.04$ m.

PIV - Transition



Airy function

Airy function[1]:

$$I(r) = \left(\frac{\pi d^2}{4\lambda z}\right)^2 \left[\frac{2J_1\left(\frac{\pi d r}{\lambda z}\right)}{\left(\frac{\pi d r}{\lambda z}\right)}\right]^2$$

1 Neiman and Shaw: Coronas and iridescence in mountain wave clouds over northeastern colorado (2003)