COMBUSTION FUNDAMENTALS

Premixed and Non-Premixed Turbulent Flames

EXAMPLE: SPARK IGNITION ENGINES

- Even though fuel is introduced as a liquid, spark-ignition engines fuels are highly volatile, and liquid has time to vaporize and thoroughly mix with air before mixture ignited by spark
- Combustion duration is an important parameter in operation of spark-ignition engines and is controlled by **turbulent flame speed** and distribution of combustion volume
- Compact combustion chambers produce short combustion durations
- Combustion duration governs lean-limit of stable operation, tolerance to exhaust gas recirculation, thermal efficiency, and production of NO_x emissions

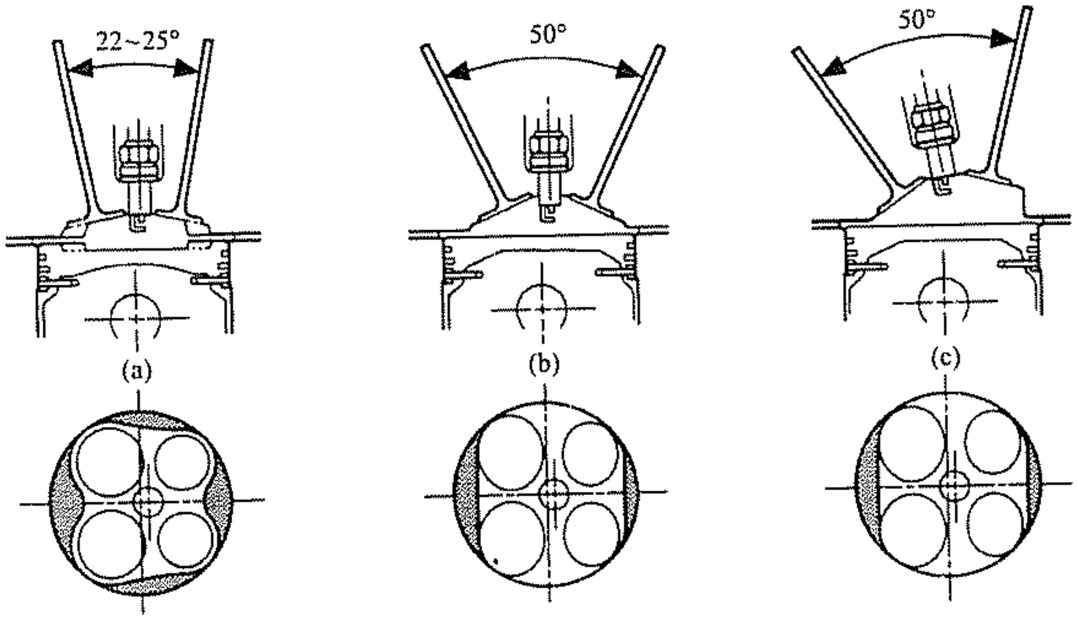
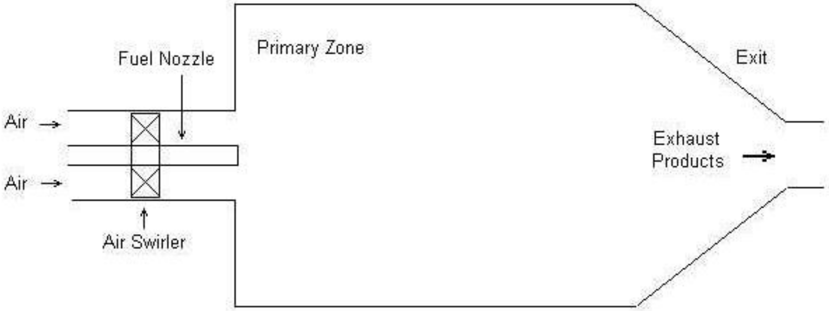


Figure 12.1 Various configurations of four-valve, spark-ignition engine combustion chambers

SOURCE: Courtesy of General Motors Corporation

EXAMPLE: GAS TURBINE ENGINES

- Engines are being more and more used for ground based power
- Current combustor design is largely influenced by the need to control soot, CO, and NO_x
- Older engines employed purely non-premixed (diffusion) combustors
  - Near stoichiometric burning primary zone
  - Secondary air to complete combustion and reduce temperature prior to entering turbine
- Some current designs use some premixing to avoid high temperature, NO_x formation zones
  - However, there are drawbacks with this design:
    - Flame stability
    - CO emissions
    - Ratio of maximum to minimum flow rates (called turndown ratio)



LPP Combustor
LPP: Lean premixed prevaporized

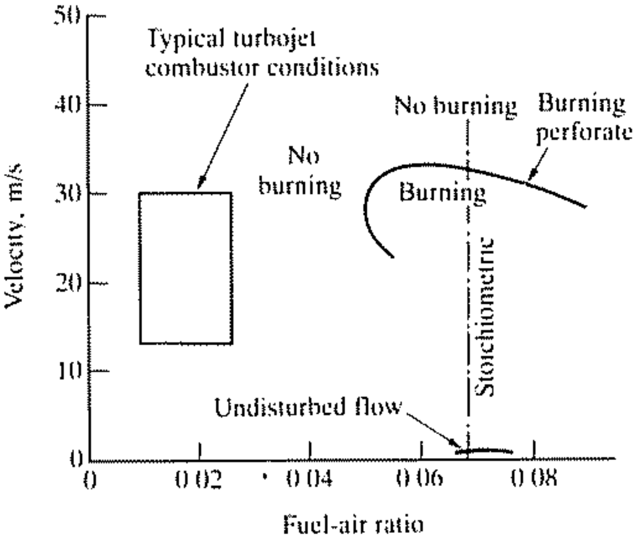


FIGURE 6.24 Dependence of flame speed on fuel–air ratio (Adapted from Olson, Childs, and Jonash [14].)

STRUCTURE OF TURBULENT PREMIXED FLAMES

- Instantaneous superimposed contours of convoluted thin reaction zones
  - – Obtained using schlieren photography at different instants in time
  - – Large folds near top of flame
  - – Position of reaction zone moves rapidly in space, producing a time-averaged view that gives appearance of a thick reaction zone, which is called turbulent flow brush
  - – Instantaneous view shows that actual reaction front is relatively thin, as in laminar premixed flame
    - Sometimes referred to as laminar flamelets

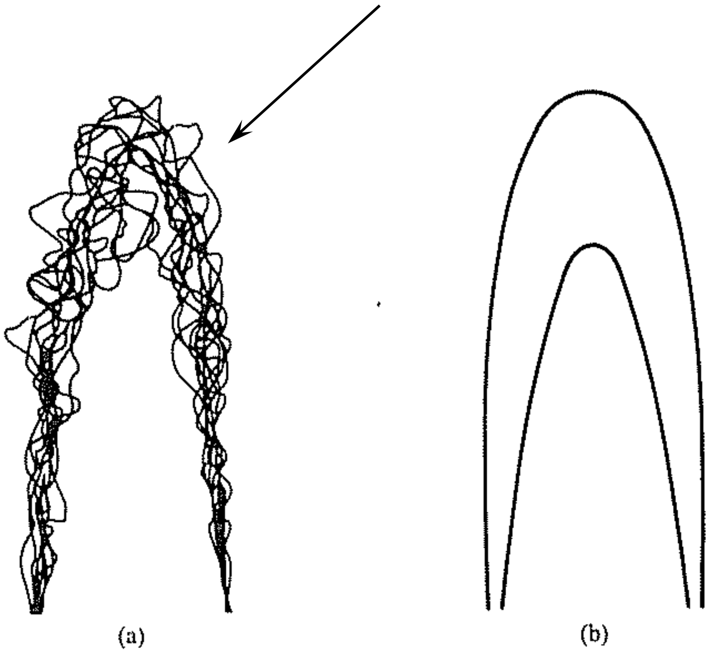


Figure 12.6 (a) Superposition of instantaneous reaction fronts obtained at different times (b) Turbulent flame "brush" associated with a time-averaged view of the same flame

SOURCE: (a) After Ref. [15] from Ref [19], reprinted by permission of Academic Press

DEFINITION OF TURBULENT FLAME SPEED, S_t

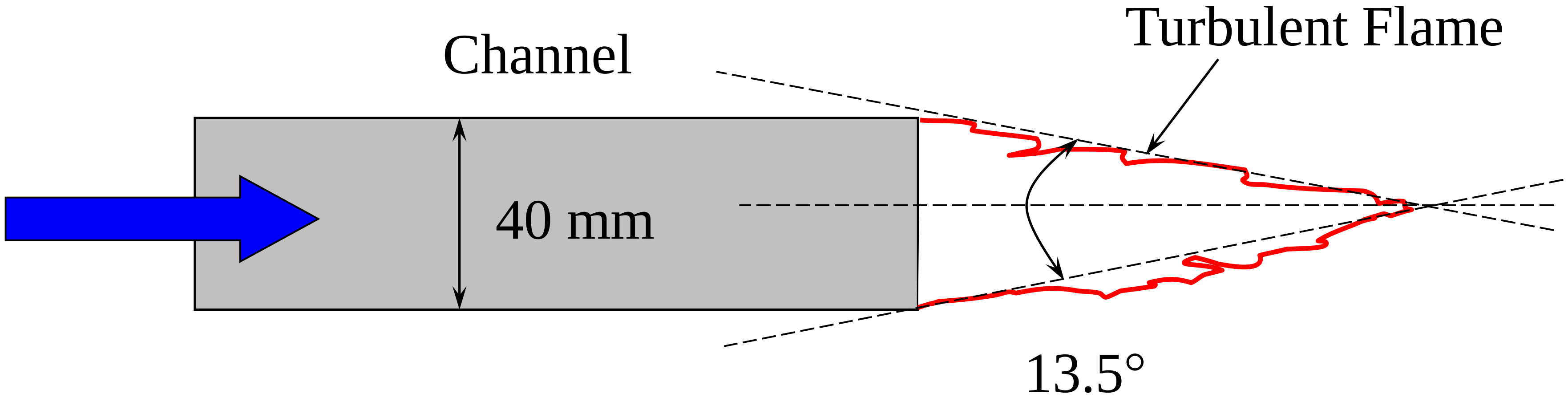
- Recall that **laminar flames** have a propagation velocity, S_L, that depends uniquely on thermal and chemical properties of the mixture
- **Turbulent flame** flames have a propagation velocity that depends on the character of flow, as well as on mixture properties
- For an observer traveling with the flame, we can define a turbulent flame speed, S_t, as the velocity at which unburned mixture enters the flame zone in a direction normal to the flame
  - Flame surface is represented as some time mean quantity
  - Instantaneous portions of the high temperature reaction zone may be largely fluctuating
  - Usually determined from measurements of reactant flowrates
- Turbulent flame speed can be expressed as:

$$S_t = \frac{\dot{m}}{\bar{A}\rho_u}$$

  - Experimental determinations of turbulent flame speeds are complicated by determining a suitable flame area, for what are usually thick and frequently curved flames
  - This ambiguity results in considerable uncertainty in measurements of turbulent flame velocities

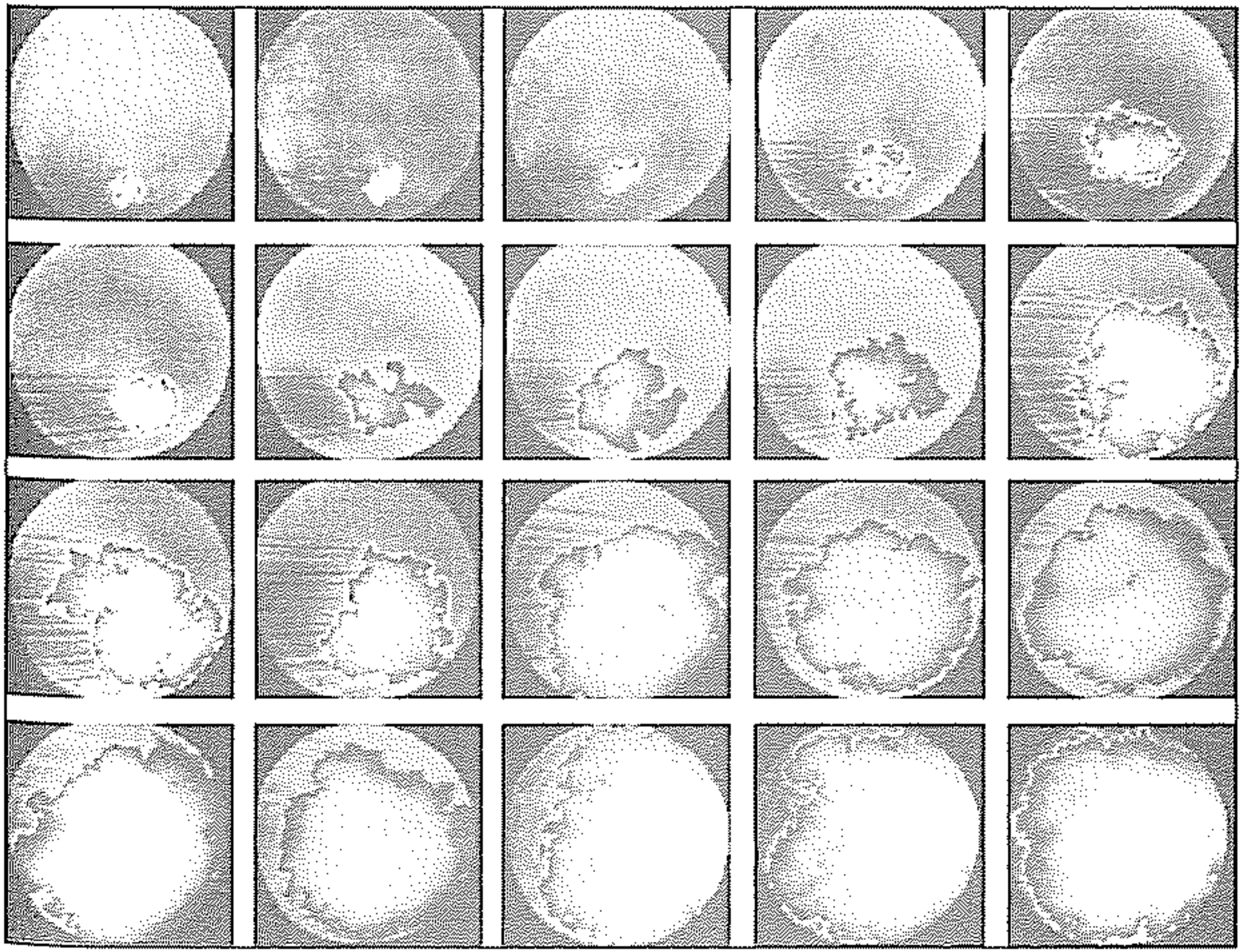
EXAMPLE: FROM EXPERIMENT

- An air-fuel mixture passes through a 40 mm by 40 mm flow channel with a flame anchored at channel exit along top and bottom walls, as shown below



  - Quartz side walls contain flame beyond exit, while top and bottom are open, so assume flame forms a wedge shape
  - Mean flow velocity is 70 m/s
  - Density of unburned gas is 1.2 kg/m^3
  - Wedge shaped flame has an angle of 13.5º, which was estimated from time averaged photographs
  - MW = 29
- Estimate turbulent burning velocity at this condition

EXAMPLE: SPARK IGNITION ENGINE VIEW



- Visualization of turbulent flame propagation in a spark-ignition engine operating at 1,200 RPM
- Images represent a planar slice through the combustion chamber with sequence starting soon after ignition (upper left photo) and proceeding until flame comes to cylinder walls
- The flame structure in these photos is in the ‘wrinkled laminar flame regime’
- Speeding up the engine to 2,400 RPM would produce a flame with ‘pockets’ or ‘islands’ of burned and unburned gases, which is given the structural name ‘Flamelets in eddies regime’

3 FLAME REGIMES

- Various length scales exist simultaneously in a turbulent flow
  - Smallest is called the Kolmogorov microscale, l_K, which represents smallest eddies in flow
    - Eddies rotate rapidly and have high vorticity (ω = DEL x V), which results in dissipation of fluid kinetic energy into internal energy (fluid friction results in a temperature rise of fluid)
  - Integral scale, l_0, characterizes largest eddies
- Basic structure of turbulent flame governed by relationships of l_K and l_0 to laminar flame thickness, δ_L
- Laminar flame thickness characterizes thickness of reaction zone controlled by molecular (not turbulent) transport of heat and mass

1. **Wrinkled laminar flame regime: $\delta_L \leq l_K$**
   - When the flame thickness is much thinner than the smallest scale of turbulence, the turbulent motion can only wrinkle or distort the thin laminar flame zone
   - Criterion for existence of a wrinkled laminar flame is referred to as **Williams-Klimov criterion**
2. **Distributed reaction regime: $\delta_L > l_0$**
   - If all scales of turbulent motion are smaller than reaction zone thickness, transport within reaction zone is no longer governed solely by molecular processes, but also by turbulence
   - Criterion for existence of a distributed reaction zone is called **Damköhler criterion**
3. **Flamelets-in-eddies regime: $l_0 > \delta_L > l_K$**

DAMKÖHLER NUMBER, Da

- Important dimensionless number in combustion, Da
- Represents a ratio of characteristic flow time to characteristic chemical time = τ_{flow}/τ_{chem}
- In premixed flames, the following time scales are particularly useful
  - Flow time, $\tau_{flow} \equiv l_0/v'_{RMS}$
  - Chemical time based on a laminar flame, $\tau_{chem} \equiv \delta_L/S_L$

$$Da = \frac{\left(\dfrac{l_0}{v'_{RMS}}\right)}{\left(\dfrac{\delta_L}{S_L}\right)} = \left(\frac{l_0}{\delta_L}\right)\left(\frac{S_L}{v'_{RMS}}\right)$$

- IF Da >> 1 reaction rates are very fast in comparison with fluid mixing rates
  - Called fast chemistry regime
- IF Da << 1 reaction rates are slow in comparison with mixing rates

- Note if fix length scale ratio, Da falls as turbulence intensity goes up

GOVERNING NON-DIMENSIONAL NUMBERS

$$\frac{l_K}{\delta_L}$$

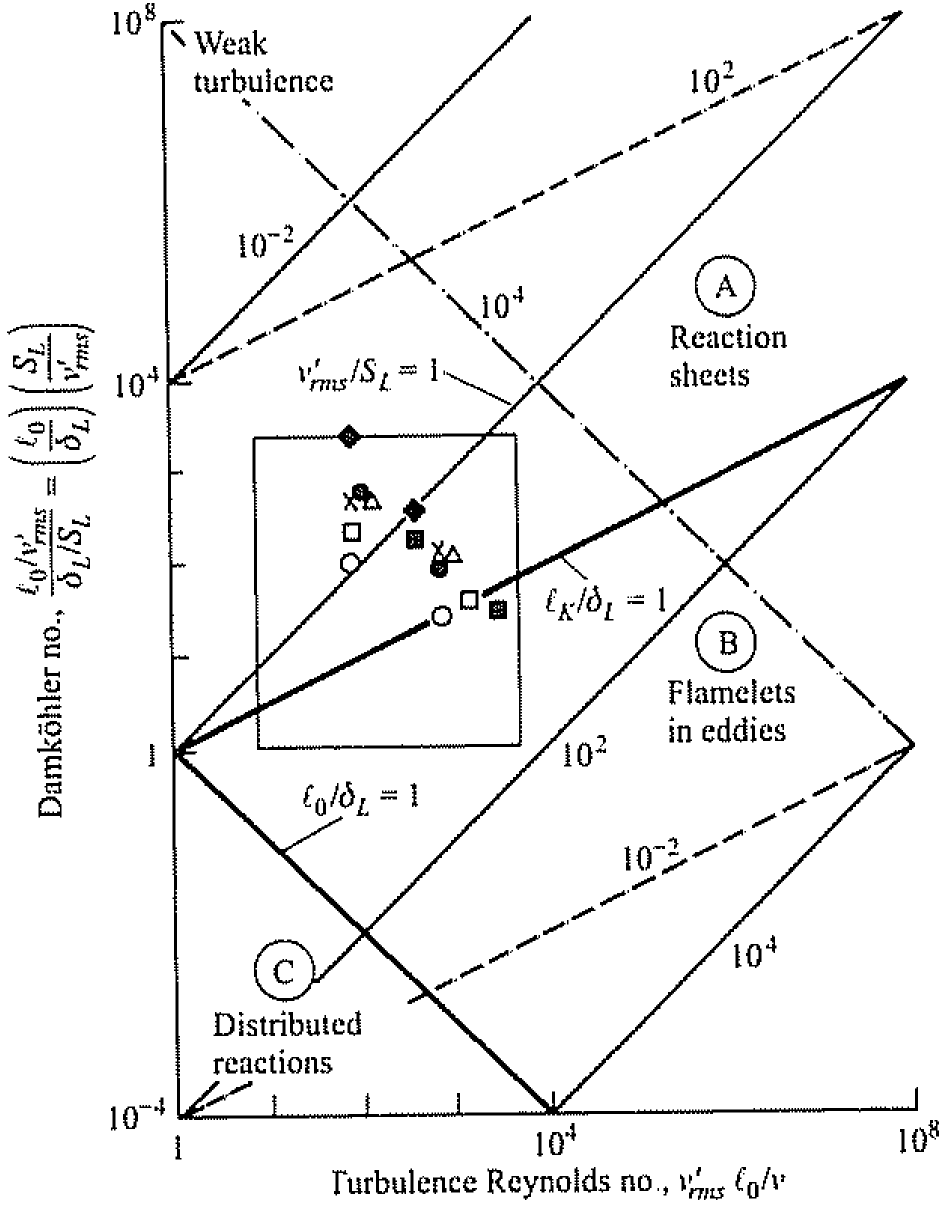
$$\frac{l_0}{\delta_L}$$

$$\mathrm{Re}_{l_0} \equiv \frac{v'_{RMS} l_0}{\nu}$$

$$Da = \frac{l_0 / v'_{RMS}}{\delta_L / S_L} = \left(\frac{l_0}{\delta_L}\right)\left(\frac{S_L}{v'_{RMS}}\right)$$

$$\frac{v'_{RMS}}{S_L}$$

IMPORTANT PARAMETERS CHARACTERIZING TURBULENT PREMIXED COMBUSTION



- What flame regime do practical devices fall under?
- Conditions satisfying Williams-Klimov criterion for wrinkled flames lie above solid line ($l_K = \delta_L$)
- Conditions satisfying Damköhler criterion for distributed reactions fall below solid line ($l_0 = \delta_L$)
- <u>Thin reaction sheets</u> can only occur for Da > 1, depending on Re, which indicates that regime is characterized by fast chemistry as compared with fluid mixing
- Box shows spark ignition engine data

COMMENTS ON WRINKLED LAMINAR FLAME REGIME

- Chemical reactions occur in thin sheets, Da > 1, fast chemistry region
- Only effect of turbulence is to wrinkle flame, resulting in an increased flame area

$$\frac{S_t}{S_L} = 1 + \frac{v'_{RMS}}{S_L}$$ Damköhler

$$\frac{S_t}{S_L} = 3.5\left(\frac{v'_{RMS}}{S_L}\right)^{0.7}$$ Klimov

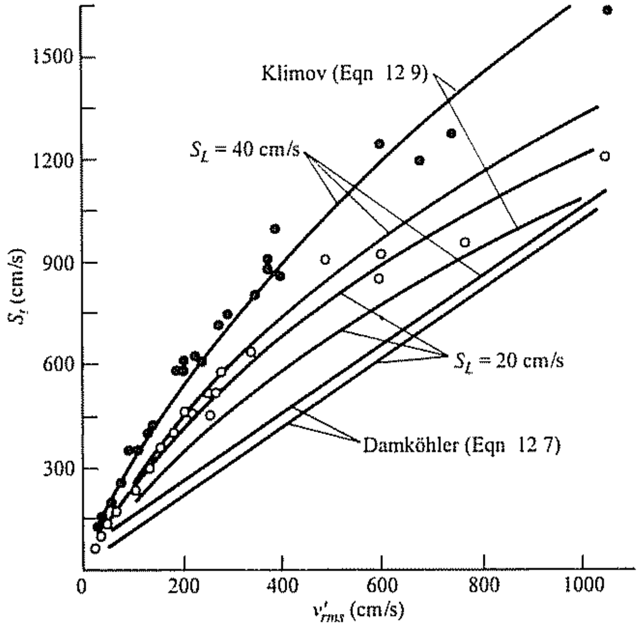


Figure 12.10 Experimental data for S_t versus v'_{rms} compared with wrinkled laminar-flame theories of turbulent flame propagation

SOURCE: Data from Ref [23]

- Example: Laser anemometry is used to measure the mean and fluctuating velocities in a spark ignition engine. Estimate the turbulent flame speed for v'_{RMS} = 3 m/s, P = 5 atm, T_u = 500 °C, ϕ = 1.0 for a propane-air mixture, and the mass fraction of the residual burned gases mixed with fresh air is 0.09.

FLAME SPEED CORRELATIONS FOR SELECTED FUELS

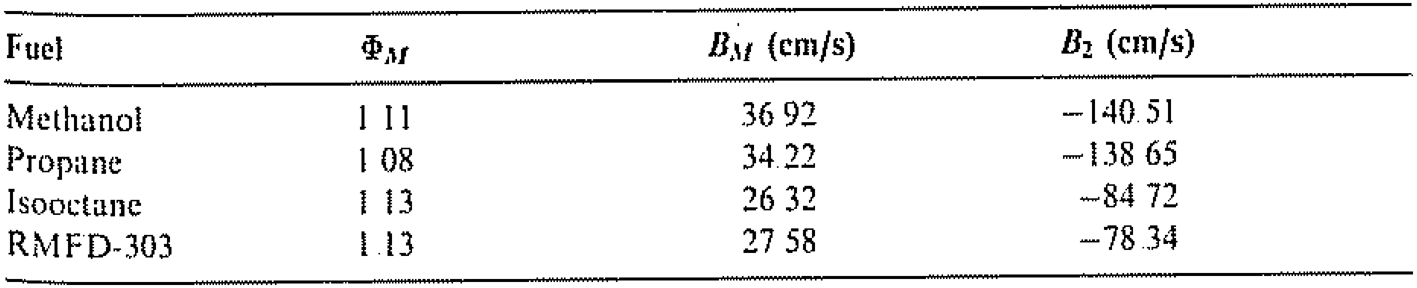
- One of most useful correlations for laminar flame speed, S_L, given by Metghalchi and Keck
  - Determined experimentally over a range of temperatures and pressures typical of those found in reciprocating IC engines and gas-turbine combustors

$$S_L = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}\left(1-2.1Y_{dil}\right)$$

$$S_{L,ref} = B_M + B_2\left(\phi-\phi_M\right)^2$$

$$\gamma = 2.18 - 0.8(\phi - 1)$$

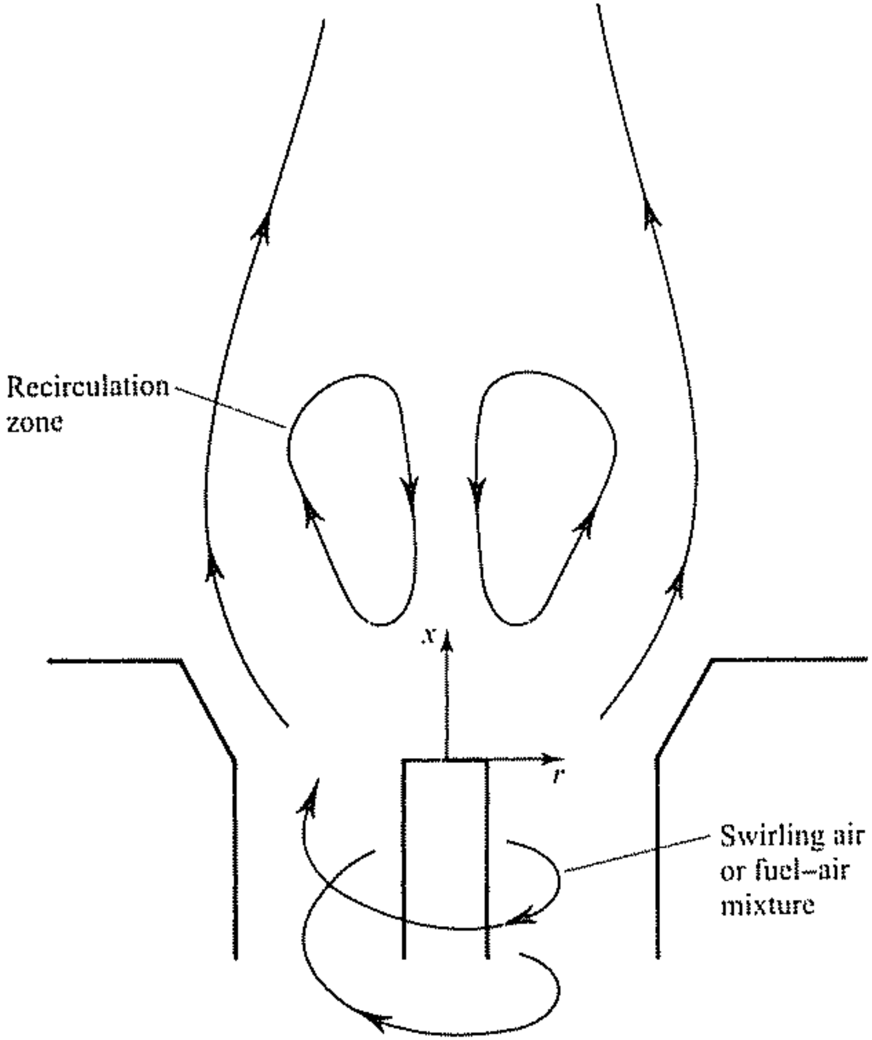
$$\beta = -0.16 + 0.22(\phi - 1)$$



Fuel	Φ_M	B_M (cm/s)	B_2 (cm/s)
Methanol	1.11	36.92	−140.51
Propane	1.08	34.22	−138.65
Isooctane	1.13	26.32	−84.72
RMFD-303	1.13	27.58	−78.34

- EXAMPLE: Employ correlation of Metghalchi and Keck to compare laminar flame speed gasoline (RMFD-303)-air mixtures with $\phi = 0.8$ for 3 cases:
  1. At reference conditions of T = 298 K and P = 1 atm
  2. At conditions typical of a spark ignition engine operating at T = 685 K and P = 18.38 atm
  3. At same conditions as (2) but with 15 percent (by mass) exhaust gas recirculation

INFLUENCE OF SWIRL



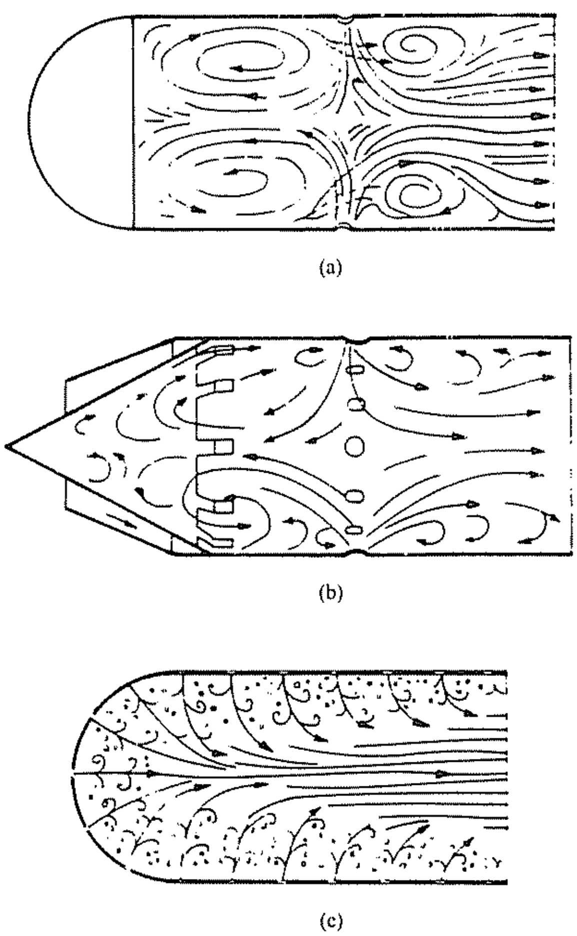


Figure 12.17 Flow patterns for can combustors with (a) single row of holes with enclosed end, (b) shrouded cone, and (c) multiple rows of holes

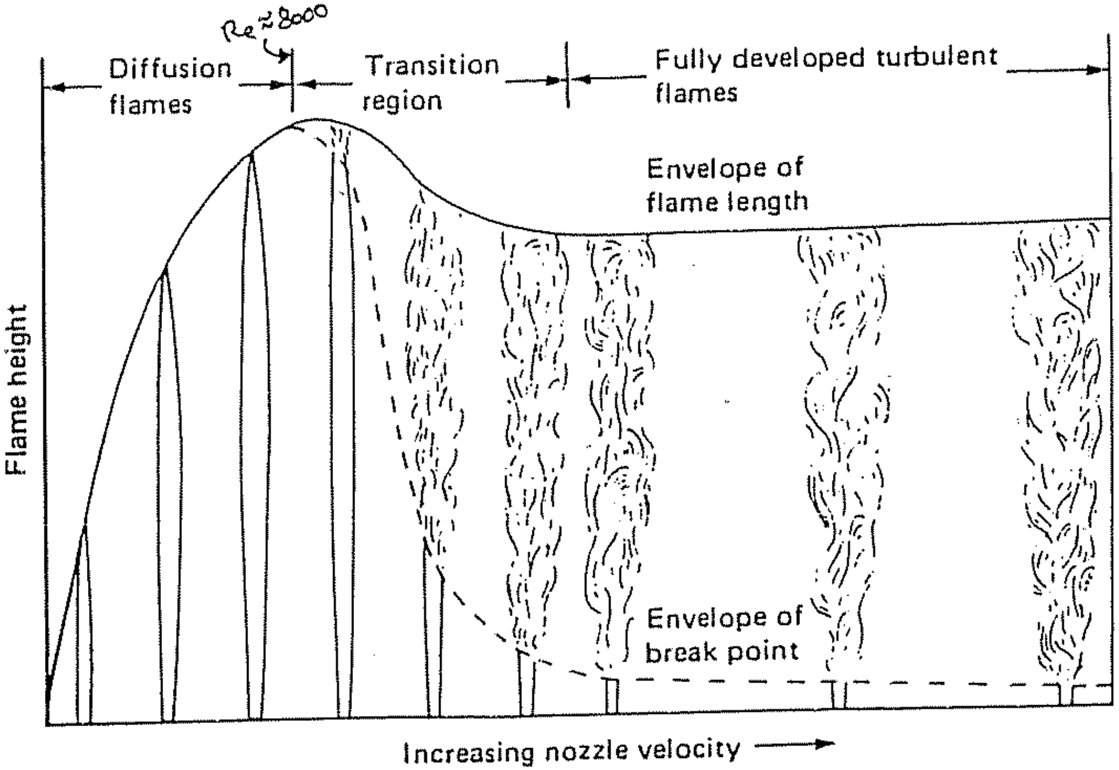
[SOURCE: From Ref [31], reprinted by permission of The Combustion Institute

OVERVIEW: TURBULENT NON-PREMIXED (DIFFUSION) FLAMES

- Turbulent non-premixed flames are employed in most practical devices as they are easier to control
- With pollutants a major concern, this advantage can become a liability
  - Less ability to control pollutant formation or ‘tailor’ flow field

- Examples
  - For low NOx in a gas turbine combustor usually new trend is to use premixed primary zones
  - Flames stabilized behind bluff bodies in afterburners for military aircraft
  - Liquid fuel sprays in diesel engines

- Engineering challenges
  - Flame shape and size
  - Flame holding and stability
  - Heat transfer
  - Pollutant emissions



COMMENTS ON JET FLAMES

- Turbulent non-premixed flames also have wrinkled, contorted and brushy looking edges, just like premixed flames
- Non-Premixed flames are usually more luminous than premixed flames due to soot within the flame
- No universal definition of flame length
  - Averaging of individual flame lengths from photographs
  - Measuring location of average peak centerline temperature using thermocouples
  - Measuring location where mean mixture fraction on axis is stoichiometric using gas sampling
  - In general, visible flame lengths tend to be larger than those based on temperature or concentration measurements

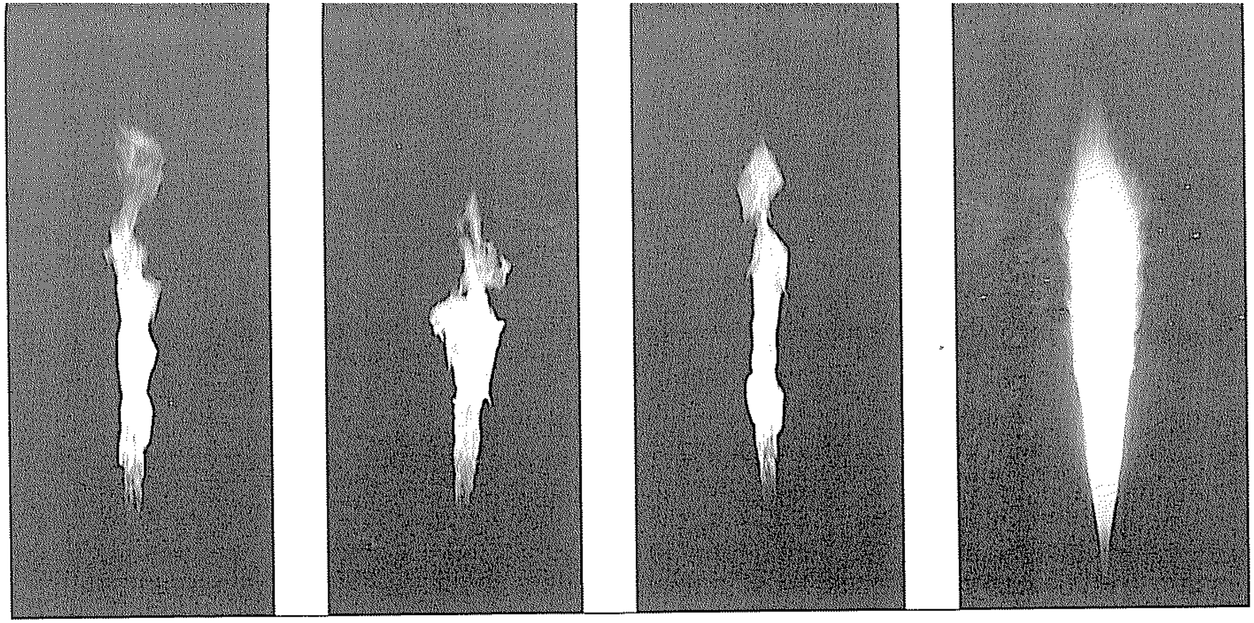


Figure 13.3 Instantaneous and time-averaged photographs of turbulent jet diffusion flames (C_2H_4–air, $d_j = 2.18$ mm). Because of the low luminosity at the base of the flame, this region is not visible on the instantaneous images (the first three photographs).

FACTORS THAT AFFECT FLAME LENGTH, L_f

- Factors affecting flame length (vertical flames issuing into a still environment)
  - Relative importance of initial jet momentum flux and buoyant forces acting on flame, Fr
    - Recall Froude number, Fr, was used to establish momentum controlled vs. buoyancy controlled flow regimes for laminar jet flames
    - Fr >> 1: flames are dominated by initial jet momentum, which controls mixing and velocity field within flame
    - Fr << 1: flames are dominated by buoyancy
  - Stoichiometric mixture fraction, $f_s = 1/((A/F)_s + 1)$
  - Ratio of nozzle fluid to ambient gas density, ρ_e/ρ_∞
  - Initial jet diameter, d_j

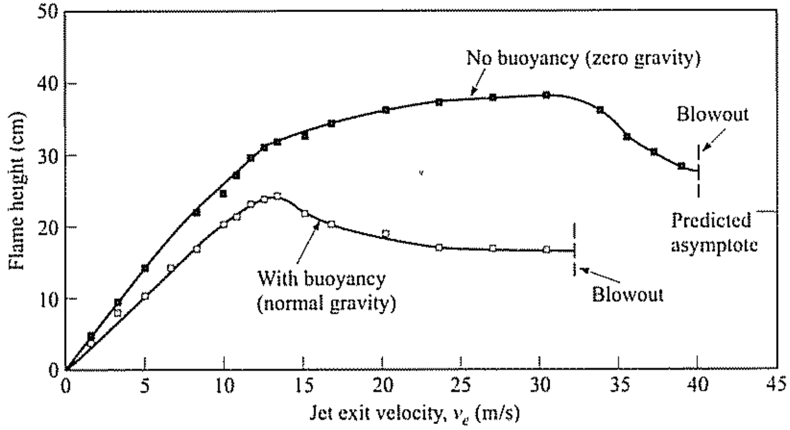


Figure 13.11 Comparison of jet flame heights with and without buoyancy (C_3H_8–air, $d_j = 0.8$ mm) Nonbuoyant conditions result from tests being conducted with near-zero ($< 10^{-5}$ g) gravitational acceleration Flames are nominally laminar at exit velocities up to approximately 10 m/s.

SOURCE: Data from Bahadori *et al* [19]

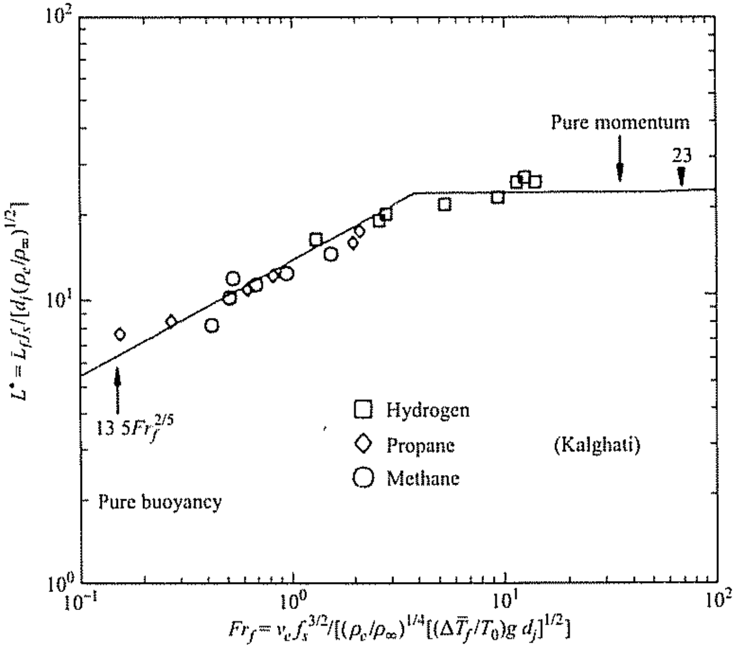


Figure 13.12 Flame lengths for jet flames correlated with flame Froude number

SOURCE: Reprinted by permission of Elsevier Science, Inc , from Ref. [15]. © 1993, The Combustion Institute

USEFUL CORRELATIONS AND EXAMPLE

$$Fr = \frac{v_e f_s^{1.5}}{\left(\frac{\rho_e}{\rho_\infty}\right)^{0.25}\left[\frac{\Delta T_f}{T_\infty} g d_j\right]^{0.5}}$$

Useful definition of Fr

ΔT_f = temperature rise from combustion

$$d_j^* = d_j\left(\frac{\rho_e}{\rho_\infty}\right)^{0.5}$$

Combination of density ratio and jet diameter

Called momentum diameter

$$L^* \equiv \frac{L_f f_s}{d_j\left(\frac{\rho_e}{\rho_\infty}\right)^{0.5}} = \frac{L_f f_s}{d_j^*}$$

Dimensionless flame length, L^*

From correlated data (on previous slide)

$$L^* = \frac{13.5 Fr^{2/5}}{\left(1+0.07Fr^2\right)^{1/5}}$$

Buoynacy dominated regime, $Fr < 5$

$$L^* = 23$$

Momentum dominated regime

- Simple Example: Estimate flame length for a propane jet flame in air at ambient conditions. Propane mass flow rate is $3.7\text{x}10^{-3}$ kg/s and nozzle exit diameter is 6 mm. Propane density is 1.85 kg/m^3

LIFTOFF AND BLOWOUT

Kalghatgi correlation to estimate blowout flow rate for jet flames

$$\frac{v_e}{S_{L,\max}}\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5} = 0.017\,\mathrm{Re}_H\left(1-3.5x10^{-6}\,\mathrm{Re}_H\right)$$

$$\mathrm{Re}_H = \frac{\rho_e S_{L,\max} H}{\mu}$$

$$H = 4\left[\frac{Y_{F,e}}{Y_{F,stoic}}\left(\frac{\rho_e}{\rho_\infty}\right)^{0.5} - 5.8\right]d_j$$

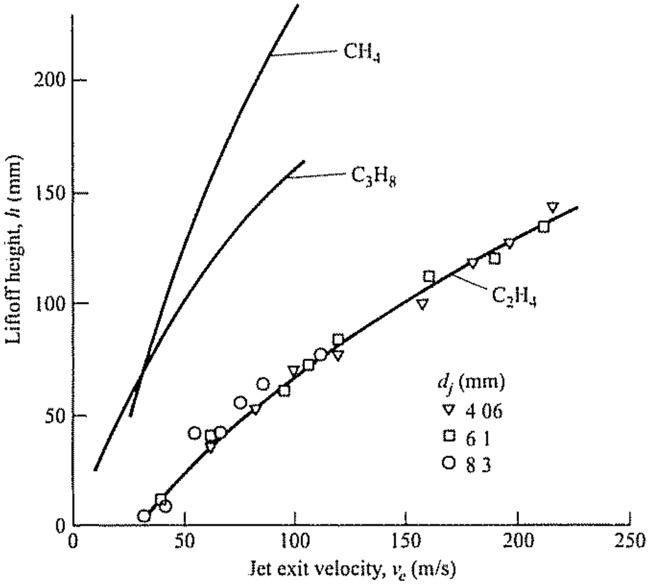


Figure 13.16 Liftoff height versus jet exit velocity for methane, propane, and ethylene jet flames.

SOURCE: After Kalghatgi [34]

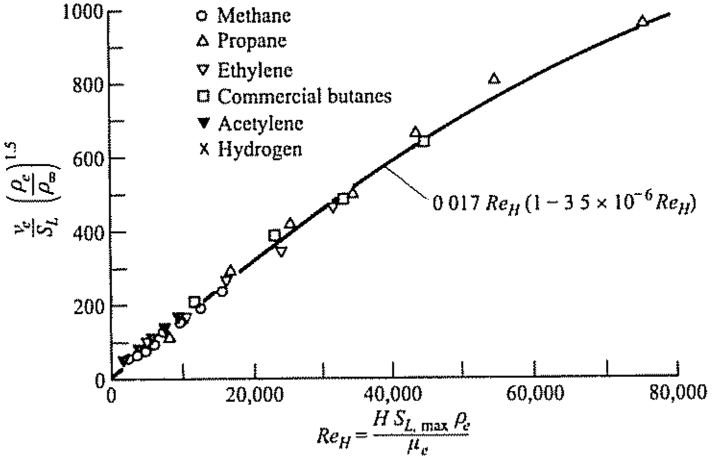


Figure 13.17 Universal blowout stability curve from Kalghatgi [35]

SOURCE: Reprinted with permission © 1981, Gordon & Breach Publishers

SIMPLE EXAMPLES CONTINUED

- From previous: Estimate flame length for a propane jet flame in air at ambient conditions.
  - Propane mass flow rate is 3.7×10^{-3} kg/s and nozzle exit diameter is 6 mm
  - Propane density at nozzle exit is 1.85 kg/m^3

- For same heat release rate and nozzle exit diameter, determine flame length when fuel is methane and compare with propane flame length
  - Density of methane is 0.6565 kg/m^3

- For propane jet flame, determine blowoff velocity and estimate liftoff height at incipient blowoff condition
  - Viscosity of propane is 8.26×10^{-6} N s/m^2.
  - To estimate liftoff height, use figure 13.16 on previous slide