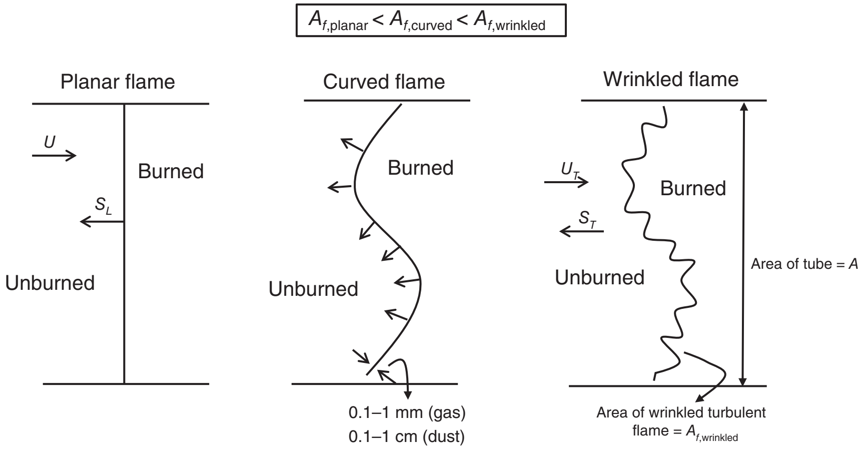


Figure 1.8 Planar, curved, and wrinkled flame. The area of the flame increases as the flame becomes wrinkled because of instabilities and turbulence effects. The laminar burning velocity and turbulent burning velocity are related as $S_L A_{f,\text{wrinkled}} = S_T A$, where S_L = laminar burning velocity, S_T = turbulent burning velocity, A is the area of the planar flame, and $A_{f,\text{wrinkled}}$ = surface area of the turbulent flame.

present and the flame is always distorted and may not even be one contiguous surface.

Finally, a note on the case with a propagating flame in a confined enclosure (either completely confined or with a vent as shown in Figure 1.7c) is warranted. In this case, the laminar burning velocity S_L will increase as the temperature of the unburned gas increases with compression and decreases with an increase in pressure as shown in Figure 1.9a,b. However, the influence of pressure is not significant given the range of pressure increase observed in building explosion accidents because the buildings cannot withstand high pressures. For example, as discussed

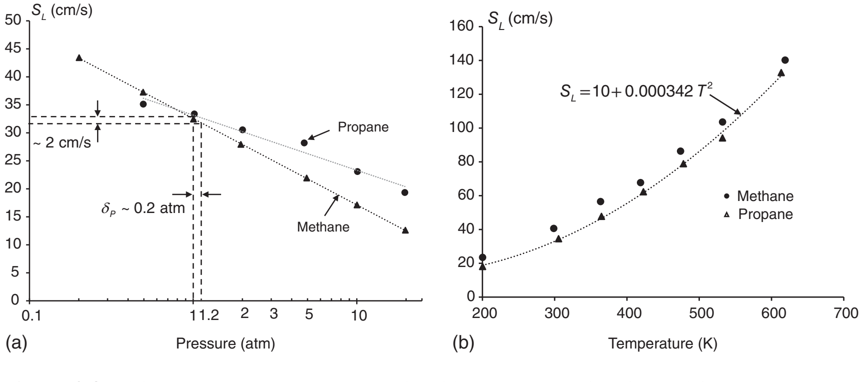


Figure 1.9 (a) Laminar burning velocity (cm/s) vs. pressure (atm) and (b) Laminar burning velocity (cm/s) as a function of unburned gas temperature T_u (K). Source: Adapted from Zabetakis [7].

earlier, a brick wall fails at an overpressure of 0.14 atm. The consequent reduction in burning velocity is only 5–10% and can be ignored (Figure 1.9a). However, unburned gas temperature, T_u, can easily increase to 700 K, thereby causing an increase in the burning velocity by nearly three to four times (Figure 1.9b).

Example 1.2 A stoichiometric mixture of methane–air at 298 K and 1 atm initially is ignited in a closed spherical vessel. Evaluate the adiabatic flame temperature. Also, evaluate the final pressure inside the vessel. Compare the result with adiabatic flame temperature for methane–air flame propagation in a tube that is open at both ends.

Solution

The solution to this problem requires the student to go through Appendix A covering basic chemistry and thermodynamics necessary to solve many problems discussed in this book. For methane–air mixture in a closed vessel, the adiabatic flame temperature is evaluated using the first law of thermodynamics (see Appendix A), which can be simplified to state that there is no change in internal energy between reactants and products, as there is no heat loss (adiabatic). Thus,

$$U_u = U_b$$

where U is internal energy, and subscripts u and b represent unburned reactants and burned product gasses, respectively. The stoichiometric reaction for methane is shown below:

$$CH_4 + 2(O_2 + 3.76N_2) \longrightarrow CO_2 + 2H_2O + 7.52N_2$$

Internal energy of unburned gas can be written in terms of enthalpies as:

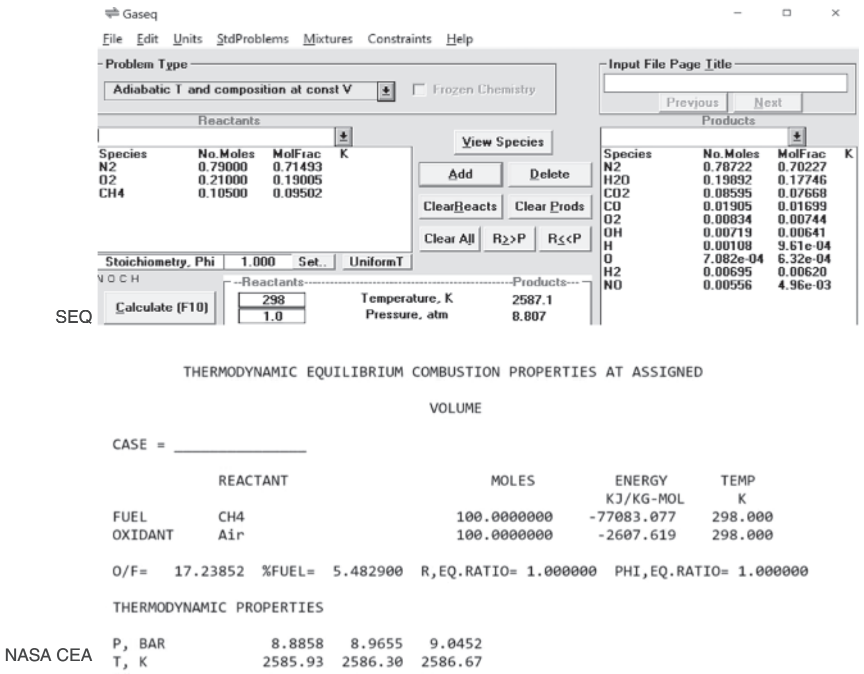
$$\begin{aligned} U_u &= H_u - p_u V = H_u - n_u R T_u \\ &= \sum n_i h_i - RT \sum n_i = [1(-74831) + 0 + 0] - 8.314 \\ &\quad \times 298 \times (1 + 2 + 2 \times 3.76) \\ &= -100\,895 \text{ kJ} \end{aligned}$$

where H is the enthalpy, n is the number of moles, R is the universal gas constant, and T is the temperature.

Internal energy of burned gas:

$$\begin{aligned} U_b &= H_b - p_b V = H_b - n_b R T_b \\ &= \sum n_i h_i - RT \sum n_i = \sum n_i (h_o + C_p(\Delta T)) - RT \sum n_i \\ &= [1(-393\,546 + 56.21(T_b - 298) + 2(-241\,845 + 43.87(T_b - 298)) \\ &\quad + 7.52 \times (0 + 33.71(T_b - 298))] - 8.314 \times T_b \times (1 + 2 + 2 \times 3.76) \\ &= -877\,236 - 118\,440 + 309.9 \times T_b \end{aligned}$$

Equating the internal energy, we get $T_b = 2887$ K. It should be noted that the values obtained using GASEQ [3] and NASA CEA are 2587 and 2586 K, respectively. Figure 1.10 shows snapshots from GASEQ and NASA CEA. The calculated value of



Problem Type: Adiabatic T and composition at const V
☐ Frozen Chemistry

Input File Page Title:

```
Reactants
Species     No.Moles   MolFrac    K
N2          0.79000    0.71493
O2          0.21000    0.19005
CH4         0.10500    0.09502
```

Stoichiometry, Phi: 1.000

NOCH

```
Products
Species     No.Moles   MolFrac    K
N2          0.78722    0.70227
H2O         0.19892    0.17746
CO2         0.08595    0.07668
CO          0.01905    0.01699
O2          0.00834    0.00744
OH          0.00719    0.00641
H           0.00108    9.61e-04
O           7.082e-04  6.32e-04
H2          0.00695    0.00620
NO          0.00556    4.96e-03
```

```
--Reactants-----------------------------------Products---
 298          Temperature, K          2587.1
 1.0          Pressure, atm           8.807
```

```
          THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED

                                    VOLUME

 CASE = _______________

             REACTANT                          MOLES          ENERGY      TEMP
                                                              KJ/KG-MOL      K
 FUEL        CH4                           100.0000000     -77083.077    298.000
 OXIDANT     Air                           100.0000000      -2607.619    298.000

 O/F=   17.23852  %FUEL=  5.482900  R,EQ.RATIO= 1.000000  PHI,EQ.RATIO= 1.000000

 THERMODYNAMIC PROPERTIES

 P, BAR            8.8858   8.9655   9.0452
 T, K             2585.93  2586.30  2586.67
```

Figure 1.10 Snapshots of GASEQ, Source: Morley [3], Gaseq and NASA CEA code by NASA [18] for calculating constant volume flame temperature and composition for a methane–air reaction at stoichiometric conditions.

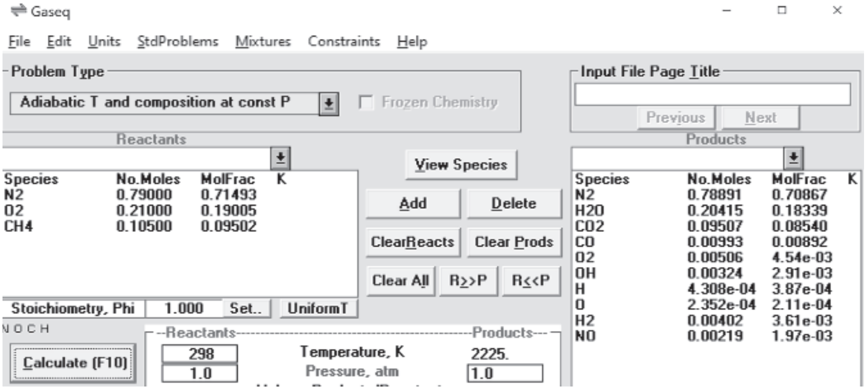
2887 K is higher than the numerical solvers because of the assumptions involved in the calculation: (i). Constant specific heat for species, and (ii) complete combustion of fuel to form CO_2 and H_2O as products.

The final pressure is evaluated as $P_b = P_u \times \frac{T_b}{T_u} = 1 \times \frac{2887}{298} = 9.7$ atm. This value as obtained from GASEQ and NASA CEA is about 8.9 atm.

For flame propagation in a tube open at both ends, the adiabatic flame temperature is evaluated at constant pressure. By using first law of thermodynamics, enthalpy of the reactants and products remains the same. Hence,

$$H_u = H_b => [1(-74831) + 0 + 0] = [1(-393546 + 56.21(T_b - 298)) \\ + 2(-241845 + 43.87(T_b - 298)) + 7.52 \times (0 + 33.71(T_b - 298))]$$

Hence, $T_b = 2317$ K. The value obtained from GASEQ is 2225 K. Again, this value is lower because we did not account for the variation of specific heat with temperature and dissociation of product species (mostly conversion of CO_2 to CO). Figure 1.11 shows a snapshot of the GASEQ code using adiabatic temperature and composition at constant pressure this time.



Problem Type: Adiabatic T and composition at const P

Input File Page Title:

Reactants

Species	No.Moles	MolFrac	K
N2	0.79000	0.71493	
O2	0.21000	0.19005	
CH4	0.10500	0.09502	

Stoichiometry, Phi: 1.000

Products

Species	No.Moles	MolFrac	K
N2	0.78891	0.70867	
H2O	0.20415	0.18339	
CO2	0.09507	0.08540	
CO	0.00993	0.00892	
O2	0.00506	4.54e-03	
OH	0.00324	2.91e-03	
H	4.308e-04	3.87e-04	
O	2.352e-04	2.11e-04	
H2	0.00402	3.61e-03	
NO	0.00219	1.97e-03	

--Reactants--		--Products--
298	Temperature, K	2225.
1.0	Pressure, atm	1.0

Figure 1.11 Snapshot of GASEQ, Source: Morley [3], Gaseq, adiabatic temperature, and composition at constant pressure for a methane–air reaction at stoichiometric conditions.

Example 1.3 A stoichiometric propane–air mixture is contained in a spherical cloud initially at 300 K. Evaluate the flame speed considering a spherical flame front as shown in Figure 1.7a.

Solution

Flame speed (S_f) is given by Eq. (1.10) as

$$S_f = \frac{A_f}{A_{f,N}} \frac{T_b}{T_u} S_L,$$

Here, the unburned gas temperature is $T_u = 300\,\text{K}$. Using Table 1.1, the laminar burning velocity of propane–air at stoichiometric (S_L) = 46 cm/s, and the temperature of burned gas is assumed to be the adiabatic flame temperature given as, $T_b = T_{\text{ad}} = 2257$ K for propane–air mixture. The adiabatic flame temperature can also be calculated using GASEQ [3] or NASA CEA [18] at constant pressure for a propane–air cloud at stoichiometric conditions.

For a planar flame front,

$$A_f = A_{f,N} => \frac{A_f}{A_{f,N}} = 1.$$

Thus, flame speed $S_f = \frac{2257}{300} \times 46 = 346.07\,\text{cm/s} \sim 3.5\,\text{m/s}$.

Note that it is assumed that there is no pressure build up. If the propane–air mixture were confined, then pressure would increase and unburned gas temperature would increase because of compression. The influence of decrease in laminar burning velocity with pressure (Figure 1.10a) and the increase in laminar burning velocity with temperature (Figure 1.10b) will need to be included to obtain an accurate solution. These influences are further explored in Chapter 3.

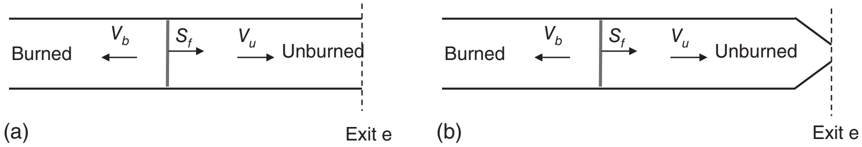


Figure 1.12 Flame propagation in a tube with (a) open ends, and (b) nozzle exit.

Example 1.4 Consider propagation of flame in a 2 cm horizontal tube open at both ends with a stoichiometric mixture of propane and air at 1 atm and 300 K initially. The planar flame propagates from left to right as shown in Figure 1.12a. Evaluate the velocity of burned gas and velocity of the flame with respect to the tube for the following exit conditions:

(i) Exit “e” shown in Figure 1.12a is open to the atmosphere at 1 atm, and $V_u = 0$
(ii) Exit “e” is a convergent nozzle of 0.2 cm diameter opening as shown in Figure 1.12b and $V_u \neq 0$.

Assume that pressure of the burned gasses is at atmospheric = 101 325 Pa for both exit conditions.

Solution

i. Figure 1.12a shows the velocities with respect to the tube, namely, the burned gas velocity (V_b), the unburned gas velocity (V_u), and the flame velocity (S_f). The subscripts u and b represent unburned and burned gas, respectively. For solving the problem, we will convert to a flame-fixed coordinate system as shown in Figure 1.13. We do this because we can easily write down the conservation equations of mass, momentum, and energy. Thus, if the coordinate system is on the flame (Figure 1.13), the unburned gasses approach the flame at the laminar burning velocity S_L, and burned gasses have a velocity of U_b.
Further, for propane–air mixture at stoichiometric proportion, $S_L = 46$ cm/s (Refer Table 1.1). From Figure 1.13, we can write:

$$U_b = S_f + V_b,$$

$$\mathrm{S_L} = S_f - V_u.$$

Assuming 1D flame propagation, the equation for conservation of mass (continuity equation) can be written as:

$$\frac{d(\rho u)}{dx} = 0 => \rho u = \text{constant}$$

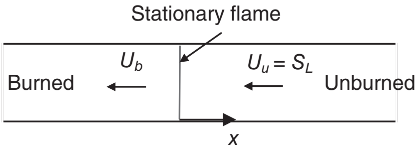


Figure 1.13 Burned and unburned gas velocities with the coordinate system on the flame.

Momentum conservation can be written as:

$$\frac{dP}{dx} + \rho u \frac{du}{dx} = 0$$

since $\frac{d(\rho u)}{dx} = 0$, $\rho u = constant$, and the momentum conservation equation can be rewritten as:

$$\frac{d(P + \rho u^2)}{dx} = 0 \Rightarrow P + \rho u^2 = \text{constant}$$

Thus, the equations that have to be solved simultaneously are:

$$\rho_u U_u = \rho_b U_b \text{ (Continuity)}$$

$$P_u + \rho_u U_u^2 = P_b + \rho_b U_b^2 \text{ (Momentum conservation)}$$

$$P_u = \rho_u \overline{R} T_u, P_b = \rho_b \overline{R} T_b \text{ (Equation of state)}$$

In these equations, $U_u = S_L = 46$ cm/s, or the velocity of the unburned gasses approaching normal to the flame. The unburned gas temperature is $T_u = 300$ K and the temperature of burned gas is the adiabatic flame temperature, $T_b = T_{\text{ad}} = 2257$ K for propane–air stoichiometric mixture. $\overline{R}$ is the gas-specific constant that can be evaluated approximately using molecular weight of nitrogen as it is the abundant species on both reactant and product side.

$$\overline{R} = \frac{8.314 \text{ J/mol-K}}{28 \text{ kg/kmol}} = 297 \text{ J/kg-K}$$

Since there is no pressure build up, the pressure of the burned gas can be assumed to be $P_b = 1$ atm. Hence, burned gas density, ρ_b, can be evaluated as:

$$\rho_b = \frac{P_b}{\overline{R} T_b} = \frac{101325}{297 \times 2257} = 0.151 \text{ kg/m}^3$$

As a result, the unknowns are ρ_u, U_b, and P_u. Using continuity equation and the momentum equation:

$$P_u + \left(\frac{P_u}{RT_u}\right) U_u^2 = P_b + \frac{(\rho_u U_u)^2}{\rho_b} \Rightarrow P_u + \frac{P_u}{RT_u} U_u^2 = P_b + \frac{1}{\rho_b}\left(\frac{P_u}{RT_u} U_u\right)^2,$$

$$P_b + \frac{P_u^2}{\rho_b}\left(\frac{S_L}{RT_u}\right)^2 - P_u\left(1 + \frac{S_L^2}{RT_u}\right) = 0,$$

$$101325 + P_u^2 \frac{1}{(0.151)}\left(\frac{0.46}{297 \times 300}\right)^2 - P_u\left(1 + \frac{0.46^2}{297 \times 300}\right) = 0.$$

The quadratic equation can be solved for P_u giving,

$$P_u = 101326.6 \text{ Pa}.$$

Observe that the unburned gas pressure, P_u equals 101326.6 Pa, which is slightly more than the burned gas pressure, which is at atmospheric (101325 Pa). However, the pressure difference is very small and $\frac{P_b}{P_u} = \frac{101325 \text{ Pa}}{101326.6 \text{ Pa}} = 0.99$. In general, $\frac{P_b}{P_u} < 1$ is the case for all deflagrations. This can be proved using the Hugoniot curve explained in combustion textbooks [19], and hence deflagrations are sometimes called as expansion waves. Note that this is opposite to detonations, which are compression waves where $\frac{P_b}{P_u} \gg 1$.

Coming back to the problem, since P_u is almost equal to atmospheric pressure at the Exit "*e*," and the exit is not confined by a nozzle, the velocity at the exit $V_e = 0\,\text{cm/s}$, pertaining to quiescent unburned reactants. As a result, $S_f \simeq S_L = 46$ cm/s. The laminar burning velocity is thus equal to the flame speed in this case.

The unburned gas density can be evaluated as:

$$\rho_u = \frac{P_u}{RT_u} = \frac{101326.6}{297 \times 300} = 1.14\,\text{kg/m}^3.$$

Observe that ρ_u is much more than the burned gas density. The burned gas velocity is

$$U_b = \frac{\rho_u U_u}{\rho_b} = \frac{1.14 \times 0.46}{0.151} = 3.47\,\text{m/s}.$$

The velocity of burned gas with respect to tube can now be calculated as:

$$V_b = U_b - S_f = 3.47 - 0.46 = 3.01\,\text{m/s},$$

Similarly, the velocity of the unburned gasses with respect to the tube is equal to:

$$V_u = S_f - S_L = 0.46 - 0.46 = 0\,\text{m/s}.$$

The solution shows that with both sides of the tube open, the flame speed is the same as the burning velocity and equals 46 cm/s. Further, the expansion of the burned gas because of combustion causes the burned gas to leave the tube at a velocity that is an order of magnitude higher and equal to 3.01 m/s. We will now examine what happens with the restriction on the unburned side with a nozzle in part (ii).

ii. When the unburned gasses vent through a convergent nozzle, they are restricted. In this case, the unburned gas velocity in lab coordinate system (V_u) can be evaluated using continuity and momentum conservation between unburned gas and Exit "e" (at 1 atm).

$$\rho_u A_t V_u = \rho_e A_e V_e \text{ (Continuity)}$$

$$P_u + \frac{\rho_u V_u^2}{2} = P_e + \frac{\rho_e V_e^2}{2} \text{(Momentum conservation)}$$

Here, A_t is the cross-sectional area of the tube and A_e is the cross-sectional area of the Exit "e" as shown in Figure 1.12b. The ratio of the two areas equals:

$$A^* = \frac{A_t}{A_e} = \frac{2 \times 2}{0.2 \times 0.2} = 100.$$

Assuming that the passage of the unburned gas through the nozzle causes no density changes, $\rho_u \simeq \rho_e$. Thus,

$$A_t V_u = A_e V_e,$$

$$V_e = \frac{A_t V_u}{A_e} = A^* V_u.$$

Substituting for V_e in the conservation of momentum,

$$P_u + \frac{\rho_u V_u^2}{2} = P_e + \frac{\rho_u}{2}[A^* V_u]^2$$
$$\rho_u V_u^2[(A^*)^2 - 1] = 2[P_u - P_e]$$
$$V_u = \sqrt{\frac{2(P_u - P_e)}{\rho_u[(A^*)^2 - 1]}} = \sqrt{\frac{2(101327\ \text{Pa} - 101325\ \text{Pa})}{1.4\ \frac{\text{kg}}{\text{m}^3}(100^2 - 1)}} = 1.7\ \text{cm/s}$$

Hence, the unburned gas velocity in the tube is $V_u = 1.7$ cm/s.
In this case, velocity of flame $= \mathrm{S}_f = S_L + V_u = 46 + 1.7 = 47.7$ cm/s with respect to the tube. Moreover, the velocity at nozzle exit $= A^* V_u = 170$ cm/s.
Velocity of burned gas with respect to the tube $= V_b = U_b - S_f = 3.47 - 0.477 = 3$ m/s.

The pressure difference created because of the slightly higher pressure on the unburned side drives the flow out of the nozzle. In the tube, the flame speed, S_f, increases by 1.7 cm/s to compensate for this flow out of the nozzle. The most important aspect is the fact that the pressure on either side of a flame in a deflagration is such that the pressure on the unburned side is higher. This difference is necessary to cause the flow of unburned fresh fuel toward the flame.

1.4 Mixture Concentration – Definition of Flammability Limits

Figure 1.14 shows that the laminar burning velocity of methane–air flame varies with equivalence ratio, whereby it is maximum for an equivalence ratio slightly greater than 1, but for lean and rich mixtures its value drops.

In fact, at less than ~1/2 stoichiometric, or more than ~3 times stoichiometric, it is not possible to sustain a self-propagating flame. Such values of $\Phi_{\min}$ or $\Phi_{\max}$ establish

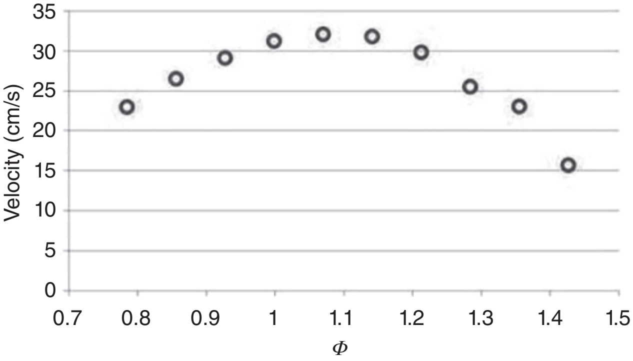


Figure 1.14 Laminar burning velocity of methane–air premixed flame at different equivalence ratios. Measurements were performed at the Worcester Polytechnic Institute (WPI) combustion laboratory using the cone angle method.

the flammability limits of a fuel–air mixture. Since S_L is a function of composition, initial temperature, and pressure, a flammability limit can be defined as the limit of one of these quantities beyond which a fuel–oxidizer mixture cannot be made to burn. The flammability limits are usually tabulated in codes and standards [9] and standard textbooks [20] and are shown in Table 1.1 for some practical fuels of interest. Extensive tabulation can be found in Coward and Jones [21] and Zabetakis [7] based on experiments performed by the Bureau of Mines in 1950–1965. An interesting point to note is that lower flammability limit (LFL) is independent of O_2/N_2 ratio in air. For example, if all the N_2 is replaced by O_2, the LFL will not change. This is because both O_2 and N_2 have the same specific heat, and thus the heat of combustion transferred to either gas will lead to the same reaction temperature. The upper flammability limit (UFL), on the other hand, depends strongly on the concentration of O_2 in air, since this limit is caused by an excess of fuel, i.e. by a deficiency of oxygen. Bartknecht [22] has also shown that the relative humidity has a perceptible influence on the width of the flammability range, with the widest range observed in extremely dry mixtures.

Figure 1.15 shows a spherical vessel [ASTM E681-09] for measuring the UFL and LFL of vapors and gasses. The gas mixture is contained in a 5 l borosilicate spherical glass vessel with a cover clamp, which is held down by light springs. There is provision for gas inlet and air inlets in the cover clamp. The uniform mixture of gas or vapor is ignited by an electric spark from the stainless steel electrodes, and the upward and outward propagation of the flame away from the ignition source is noted by visual observation. The concentration of the flammable component is varied between trials until the composition that will just sustain propagation of the flame is determined.

Flammability limits are of practical interest in safety considerations because mixtures outside of these limits can be handled without concern for ignition. For most practical applications, the flammability limits can be correlated using the heat of

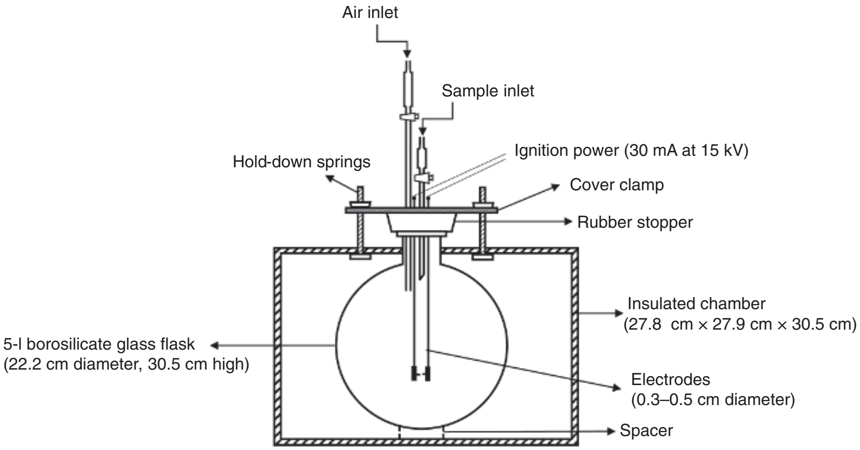


Figure 1.15 ASTM standard test method for measuring upper and lower flammability limits of gasses and vapors. Source: Adapted from Zabetakis [7].

combustion as shown by Suzuki and Koide [23, 24]

$$
\begin{aligned}
LFL &= \frac{-3.42}{\Delta H_c} + 0.569\Delta H_c + 0.0538\Delta H_c^{\,2} + 1.80 \\
UFL &= 6.30\Delta H_c + 0.567\Delta H_c^{\,2} + 23.5 \qquad (1.13)
\end{aligned}
$$

Equation (1.13) is an empirical relationship considering 123 organic materials containing carbon, hydrogen, oxygen, nitrogen, and sulfur. The heat of combustion ΔH_c is in kJ/mol and the LFL and UFL are in vol% of fuel in air.

Adding an increasing quantity of inert gas or a noncombustible mixture can also lead to a critical concentration causing a no-flame propagation. This is usually expressed in terms of a limiting oxygen concentration (LOC) and is based on the concentration of inert that needs to be added to prevent ignition of a combustible gas–air mixture. The efficiency of the inert gas is based on the quantity of heat transferred during the flame propagation and ensuring that this heat is absorbed without causing further reaction to sustain flame propagation.

Example 1.5 Estimate the LOC for butane (C_4H_{10}).

Solution

The LFL for butane is = 1.9% by volume. The overall chemical reaction of butane at stoichiometric condition is

$$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$$

The LOC can be estimated as:

$$LOC = \left[\frac{\text{moles fuel}}{\text{total moles}}\right]_{\text{LFL}} \left[\frac{\text{moles } O_2}{\text{moles fuel}}\right]_{\text{stoichiometric}} = 1.9\frac{6.5}{1} = 12.4\,\text{vol}\%O_2$$

Thus the combustion of butane can be prevented by adding an inert until the oxygen concentration is below 12.4%.

1.5 Minimum Ignition Energy (MIE) and Auto Ignition Temperature (AIT)

Some energy has to be input initially to initiate a chemical reaction. The MIE is the minimum *energy* input required to initiate combustion. Many hydrocarbons have an MIE of 0.25 mJ. This is low enough to cause ignition by electrostatic discharges due to fluid flow and static electricity. Walking across a rug on a cold winter day initiates a static discharge of around 22 mJ. An ordinary spark plug has a discharge of 25 mJ. Thus, given a flammable gas mixture, ignition is relatively easy. For a dust-air mixture, the MIE is significantly higher and can exceed 1000 mJ in some cases making ignition of dust clouds more energy intensive compared to gas clouds. We will discuss this further in Chapter 8.

MIE decreases with an increase in pressure. The pressure is the net force that gas molecules are exerting when they collide with a container's walls. High pressure means more collisions per second of gas molecules on the container and/or each

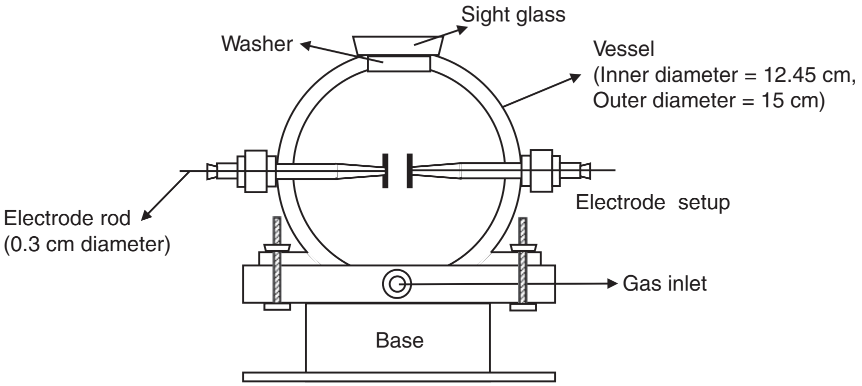


Figure 1.16 ASTM standard test method for measuring minimum ignition energy. Source: Adapted from Mitu et al. [10]/American Chemical Society.

collision is occurring with a greater force. Thus, gas molecules in a high-pressure condition are moving about very fast and therefore have higher energy. This means they will need lesser energy from an ignition source to react. The MIE is related to the burning velocity by MIE $\equiv \frac{k_u}{S_u}[T_f - T_o]$, where k_u is the thermal conductivity of the unburned gas, T_f is the flame temperature, and T_o is the ambient temperature.

The standard test method for MIE is shown in Figure 1.16 [ASTM E582-07]. A stainless steel spherical vessel with inner diameter of 12.45 cm (4.9″) is used. The gasses enter the vessel through tangential ports to enhance mixing through the induced swirl. Thin 3.175 mm (1/8″) stainless steel rods are used as electrodes and the applied voltage is increased such that a spark occurs. The flame initiation and propagation can be observed through a sight glass that is provided to ensure visual access.

The autoignition temperature is different from the MIE and denotes the minimum temperature at which a gas mixture will react spontaneously without the presence of a spark. It depends on the concentration or equivalence ratio of the gas mixture, pressure, flow condition, initial temperature, and the presence/absence of a catalyst. The ignition of vapor is also possible by adiabatic compression. For example, vapors in a gasoline engine ignite when compressed to a temperature that exceeds AIT creating engine knock. Several large accidents have been caused due to flammable vapors sucked into the intake of air compressors. Example 1.6 adapted from Crowl and Louvar [25] illustrates this mode of ignition.

Example 1.6 A lubricating oil has an AIT of 400 °C. Compute the compression ratio required to raise the temperature of air to the AIT of this oil. Assume an initial air temperature of 25 °C.

Solution

$$T = P^{(\gamma-1)/\gamma}$$

$$\Rightarrow P = T^{\gamma/(\gamma-1)}$$

$$\Rightarrow \frac{P_f}{P_i} = \left(\frac{T_f}{T_i}\right)^{\gamma/(\gamma-1)} = \left(\frac{400+273}{25+273}\right)^{1.4/0.4} = 17.3$$

Therefore, compression ratio should be kept below 17.3 × 14.7psia = 254 psia.

Lubricating oil in piston-type compressors is always found in minute amounts in the cylinder bore. Compressor operations must always be kept below the AIT of the oil to prevent explosion.

Exercise Problems

1 Due to a high-pressure steam hose breakage, air above a hexane fuel layer is compressed by 12 times ambient pressure of 1 atm. If the autoignition temperature of hexane is 487 °C (760 K) what should be the temperature of the ambient to ensure no autoignition.

2 A full propane cylinder from a camp stove leaks its contents of 1.02lb (0.464 kg) into a $12' \times 14' \times 8'$ (3.66 m × 4.27 m × 2.44 m) room at 20 °C and 1 atm. After a long time, the fuel gas and room air are well mixed. Is the mixture in the room flammable?

3 What volume of air is required to burn stoichiometrically 1 mole of propane gas, with the initial air at 25 C and with a pressure of 0.98 bar. If the pressure equals 2.2 bar, what is the volume?

4 What will be the most effective diluent to an explosive mixture of H2 to lower or prevent explosion possibility: Carbon Dioxide, Helium, Nitrogen, or Argon? Arrange in order of effectiveness.

5 Consider propagation of flame in a 2 cm diameter horizontal tube open at both ends with a stoichiometric mixture of propane and air at 1 atm and 300 K initially. The planar flame propagates from left to right as shown in Fig. 1.12a. Evaluate the velocity of burned gas, and velocity of the flame with respect to the tube for a convergent section of 0.2 cm diameter opening at the burned side of the tube. Assume that pressure of the unburned gases is at pressure of 101327 Pa.

Nomenclature

A	Area (m^2)
C_d	Orifice discharge coefficient (−)
C_P	Specific heat at constant pressure (J/kg K)
C_V	Specific heat at constant volume (J/kg K)
E	Expansion ratio $\frac{T_b}{T_u} \sim \frac{T_f}{T_u} \sim 8$ (−)
h	Entalpy per unit mass (J/g)

k	Thermal conductivity (W/m K)
m	Mass (kg)
n	Number of moles (–)
P	Pressure (N/m^2 or Pa)
r	Radius of spherical enclosure (m)
R	Universal gas constant (8.314 J/mol K)
$\overline{R}$	Gas constant for a specific gas $\frac{R}{MW}$ (J/kg K)
Re	Reynolds number (–)
S_L	Laminar burning velocity (m/s)
S_T	Turbulent burning velocity (m/s)
S_U	Unburned gas burning velocity (m/s)
S_f	Flame speed (m/s)
T	Temperature (K)
u	Velocity (m/s)
u'	Turbulent intensity (m/s)
U	Internal energy (J)
V	Volume (m^3)
W	Width (m)
X	Mole fraction (–)
Y	Mass fraction (–)

Greek Symbols

ρ	Density (kg/m^3)
β	Multiplication factor in Eq. 1.2 to account for flame acceleration because of turbulence and instabilities (–)
ϕ	Equivalence ratio (–)
γ	Ratio of specific heats ($C_P\,/C_V$)

Subscripts

a or o	Ambient
ad	Adiabatic
b	Burned
e	Exit
f	Flame
i	Initial condition
min	Minimum
max	Maximum
N	Normal
t	Total
u	Unburned

Other Notations

AIT	Auto Ignition Temperature (K)
LFL	Lower Flammability Limit (vol %)
LOC	Limiting Oxygen Concentration (vol %)
MIE	Minimum Ignition Energy (mJ)
MW	Molecular Weight (g/mol)
UFL	Upper Flammability Limit (vol%)
ΔH_c	Heat of combustion (J/kg)

References

1 Strehlow, R.A. and Baker, W.E. (1976). The characterization and evaluation of accidental explosions. *Progress in Energy and Combustion Science* 2 (1): 27–60.

2 Zalosh, R.G. (2008). Explosions. In: *Fire Protection Handbook*, 20 (ed. A.E. Cote), 2-93–2-106. NFPA.

3 Morley, C. (2005). Gaseq: a chemical equilibrium program for Windows. Ver. 0.79.

4 Carlson, G. (1973). Spherical detonations in gas-oxygen mixtures. *Combustion and Flame* 21 (3): 383–385.

5 NFPA 68 (2018).*Standard on explosion protection by deflagration venting*. National Fire Protection Association. National Fire Protection Association.

6 Babrauskas, V. (2003). *Ignition Handbook*, Issaquah, WA: Fire Science Publishers.

7 Zabetakis, M.G. (1965). *Flammability Characteristics of Combustible Gases and Vapors*. Washington DC: Bureau of Mines.

8 Barnett, H.C. and Hibbard, R.R. (1958). *Basic Considerations in the Combustion of Hydrocarbon Fuels with Air*, Report 1300. US Government Printing Office.

9 NFPA 69 (2019). *Standard on explosion prevention systems*. Quincy, MA: National Fire Protection Association.

10 Mitu, M., Razus, D., Giurcan, V., and Oancea, D. (2014). Experimental and numerical study of laminar burning velocity of ethane–air mixtures of variable initial composition, temperature and pressure. *Energy & Fuels* 28 (3): 2179–2188.

11 Bankoff, S.G., Cho, D.H., Cronenberg, A.W., Fauske, H.K., Henry, R.E., Hutcherson, M.N., Marciniak, T.J., Reid, R.C., and Thomas, G.R. (1983). Steam explosions: their relationship to LWR safety assessments (NUREG/CP–0027-Vol2).

12 Kingery, C., Keefer, J., and Day, J. (1962). *Surface Air Blast Measurements from a 100-Ton TNT Detonation*. Aberdeen Proving Ground, MD: Army Ballistic Research Lab.

13 Selby, C. and Burgan, B. (1998). Blast and fire engineering for topside structures-Phase 2. Final summary report. Steel Container Institute, Publication Number 253.

14 National Transportation Safety Board (2000). Aircraft Accident Report NTSB/AAR-00/03, PB2000-910403.

15 Taveau, J. (2012). The Buncefield explosion: were the resulting overpressures really unforeseeable? *Process Safety Progress* 31 (1): 55–71.

16 Penner, S.S. and Mullins, B.P. (1959). *Explosions, Detonations, Flammability and Ignition*. Pergamon Press London.

17 Zalosh, R. (1979). Gas explosion tests in room-size vented enclosures. *Loss Prevention* 13: 98.

18 McBride, B.J. and Gordon, S. (1996). Computer program for calculation of complex chemical equilibrium compositions and applications II. Users Manual and Program Description. NASA reference publication 1311.

19 Glassman, I. (1996). *Combustion*. San Diego, California: Academic Press.

20 Turns, S.R. (1996). *An Introduction to Combustion*, New York: McGraw-hill.

21 Coward, H.F. and Jones, G.W. (1952). *Limits of Flammability of Gases and Vapors*, Bulletin 503. Bureau of Mines, US Government Printing Office.

22 Bartknecht, W. (1989). *Explosions: Course, Prevention, Protection*. Berlin: Springer-Verlag New York.

23 Suzuki, T. and Koide, K. (1994). Correlation between upper flammability limits and thermochemical properties of organic compounds. *Fire and Materials* 18 (6): 393–397.

24 Suzuki, T. (1994). Quantitative structure-property relationships for auto-ignition temperatures of organic compounds. *Fire and Materials* 18 (2): 81–88.

25 Crowl, D.A. and Louvar, J.F. (2001). *Chemical Process Safety: Fundamentals with Applications*. Pearson Education.