Gas and Vapor Cloud Explosions

2.1 Combustion of Gases and Vapors

2.1.1 Diffusion Combustion and "Premixed" Combustion

Burning of combustible gases is well known from daily life. Propane (C_3H_8), for example, is often used for lighting, heating, and cooking where electricity is not easily available. When discussing the burning of combustible gases, it is important to distinguish between diffusion controlled burning and burning of premixed gas/air. Figure 2–1 illustrates the flame of a common gas lighter with butane (C_4H_{10}) as the fuel. The burning is limited to a narrow zone just outside the butane outlet, where the gas makes contact and mixes with the ambient air, and hence with oxygen. The burning occurs comparatively slowly, being controlled by the rate of diffusion of fuel and oxygen molecules into the reaction zone. The same type of burning takes place in a candle flame and in the flame of an oil lamp.

In a Bunsen burner, as illustrated in Figure 2–2, the situation is different. In this case, the combustible gas is first mixed well with air before becoming ignited. In the Bunsen burner, it is important that the mass flows of propane and air are adjusted to yield a propane concentration within the flammable range. Furthermore, the overall mass flow of the mixture must be below certain limits. If the flow is too high, the flame will be blown away upwards and extinguish; if it is too low, the flame will propagate downwards into the interior of the burner.
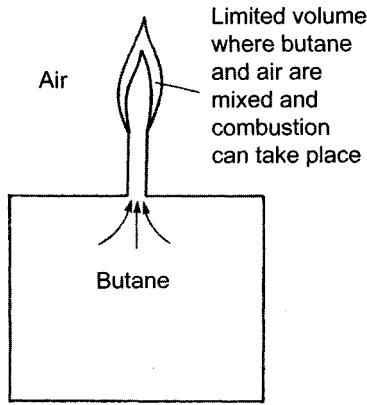
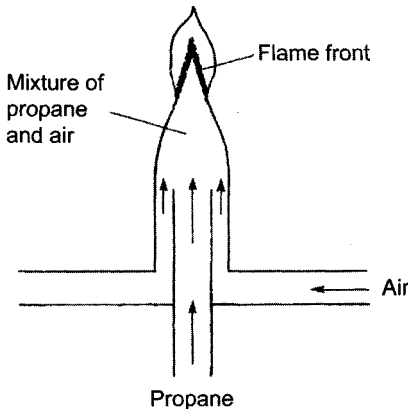**Figure 2–1   Butane lighter flame. Example of diffusion controlled burning of a combustible gas in air.**

Figure 2–2   Burning of premixed propane/air in a Bunsen burner.

2.1.2 Laminar Burning of Premixed Gas/Vapor and Air

Figure 2–3 gives experimentally determined relationships between the so-called laminar burning velocity and the concentration of combustible gas in the mixture with air for four common combustible gases.

The ideal laminar burning velocity is the lowest velocity at which a flame front can propagate through a given gas mixture (given ratio of gas to air,
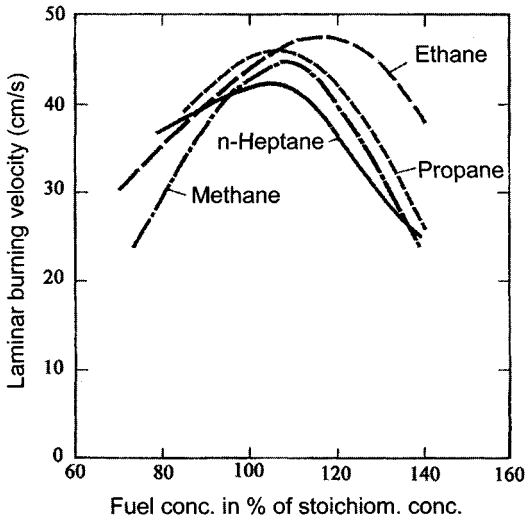
Figure 2–3   Laminar burning velocities S_u at atmospheric pressure and normal temperature for mixtures of various hydrocarbon gases and air. From Zabetakis (1965) p. 45.

given pressure and temperature). The flame zone is then a smooth, plane sheet of thickness of the order of 1 mm, traveling at constant velocity through the quiescent homogeneous gas/air mixture. The heat transfer mechanism driving the flame propagation is mainly heat conduction.

As Figure 2–3 shows, the differences between the laminar burning velocity for the various alkanes (saturated linear hydrocarbons) is relatively small, all four maximum values falling in the range 0.42–0.47 m/s. However, as illustrated by Figure 2–4, unsaturated hydrocarbons can have considerably higher maximum values.

Both Figure 2–3 and Figure 2–4 illustrate that for any combustible gas, S_u has a maximum value when the mixing ratio of fuel to air is close to the stoichiometric ratio. At the stoichiometric ratio, the ratio of fuel to oxygen is exactly what is required for all the oxygen to transform all the fuel to CO_2 and H_2O. When the fuel/air ratio moves away from the stoichiometric value, whether in the direction of leaner or richer mixtures, the value of S_u becomes systematically smaller.

Table 2–1 provides maximum experimental S_u values for some combustible gases in air.
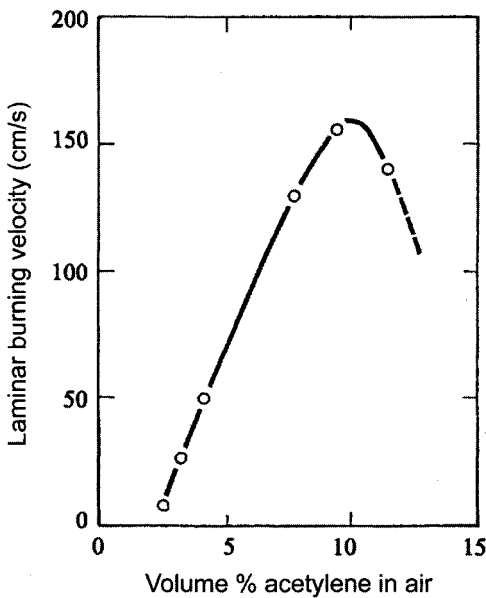
Figure 2–4   Laminar burning velocities S$_u$ for different mixing ratios of acetylene and air, at atmospheric pressure and normal temperature. From Zabetakis (1965) p. 59.

2.1.3 Flammable Concentration Ranges for Premixed Gas/Vapor and Air

2.1.3.1 General

As the fuel to air ratio is increased or decreased sufficiently, departing from the stoichiometric value, two finite limits are eventually reached beyond which the mixture is no longer able to propagate a flame. These limits bracket the flammable (or explosive) range of a given combustible gas or vapor in air. Figure 2–5 illustrates the flammability ranges in air for some gases. Because acetylene, being a very reactive compound, is able to decompose exothermically in the absence of oxygen, its upper explosion limit is in fact 100 percent. The first two columns of Table 2–2 give numerical values for the lower and upper flammability limits of a number of combustible gases and vapors in air, including those in Figure 2–5.

Table 2–1   Maximum Laminar Burning Velocities S$_u$ for Premixed Fuel/Air at Atmospheric Pressure and Normal Temperature for Some Fuels[a]

Fuel	Maximum S$_u$ [cm/s]
Alkanes	40-50
Natural gas (unspecified)	40
Acetone	43
Butylene	43
Cyclohexane	44
Bensene	48
Propylene	51
Carbon monoxide	52
Methanol	57
Propylene oxide	67
Ethylene	75
Ethylene oxide	90
Acetylene	155
Hydrogen	325

a.   Data from J.M. Kuchta, *Investigation of fire and explosion accidents in the chemical, mining and fuel related industries. A Manual.* US Bureau of Mines, Bulletin 680 (1985): 38.

It should be pointed out that the experimental determination of flammability limits is not straightforward, and results obtained using different methods may scatter. The method used in the United States is described in ASTM (2003a). The fuel/air mixture to be tested is placed in a five liter spherical glass flask with the spark gap providing the electric spark for ignition located close to the flask center. The flask is filled with a uniform mixture of the desired fuel to air ratio, followed by activation of the ignition source and visual observation of the extent of flame propagation. Flame propagation both upwards and sideways is regarded as sufficient for the mixture to be regarded as flammable, whereas flame propagation upwards only, is not regarded as sufficient. Downwards flame propagation is not regarded as a necessary requirement for the mixture to be classified as flammable. In a more recent comment, Ural (2004) points out that the Lower and Upper Flammability Limits (LFL, UFL) observed in the ASTM test are not necessarily identical with Lower and Upper Explosibility Limits (LEL, UEL) determined by other methods.
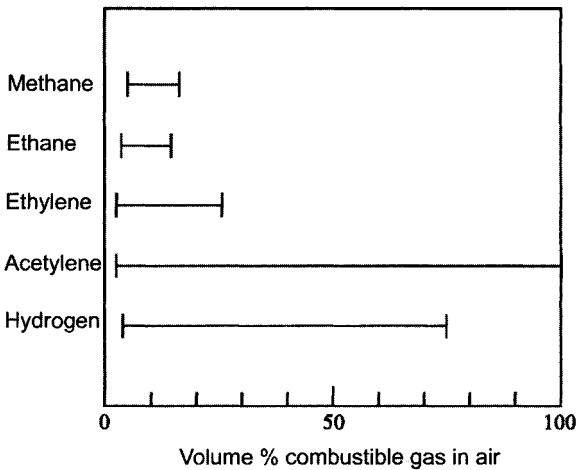
Figure 2–5   Flammable ranges for mixtures of some combustible gases and air at atmospheric pressure and normal temperature. (See also Table 2–2.)

The other data in Table 2–2 will be considered in the discussion of the respective parameters that follows.

2.1.3.2 Flash Point of a Combustible Liquid

The flash point of a combustible liquid, as defined by The Institute of Petroleum (2002), is the lowest temperature at which, in contact with air at atmospheric pressure, a flammable liquid will give off a sufficiently rich vapor for ignition to occur in the presence of an ignition source. On the condition that the ignition source is sufficiently effective, the flash point is the lowest temperature the liquid can have for the vapor/air mixture just above the liquid surface to be able to propagate a flame. There is then a direct coupling between the lower flammability limit of vapors and the flash point of their liquid phases. This is because the flash point is the temperature at which the vapor pressure of the liquid equals the partial pressure of the actual vapor at its lower flammability limit.

Flammable liquids are grouped in hazard classes on the basis of their flash points. The Institute of Petroleum (IP) classification system uses a subdivision of the main Classes II and III according to whether the condition of handling is at a temperature below or above the flash point. This is in

Table 2-2 Combustibility and Ignitability Parameters of Some Combustible Gases and Vapors in Air at Atmospheric Pressure and Normal Temperature[a]

Fuel	Flammable limits [vol. % in air]		Flash point	Min. ign. temp.	MESG	Temp. class	Gass group code
	Lower	Upper	[°C]	[°C]	[mm]		
Acetone	2.6	13.0	-19	735	1.01	T1	IIA
Acetylene	2.5	100.0	?	305	1.01	T2	IIC
Ammonia	15.0	28.0	?	630	3.18	T1	IIA
Bensene	1.3	7.9	-11	560	0.99	T1	IIA
Butadiene	2.0	12.0	-85	430	0.79	T1	IIB
Butane	1.8	8.4	-60	370	0.98	T2	IIA
Butylalcohol	1.7	12.0	29	359	0.91	T2	IIA
Cyclohexane	1.3	7.8	-18	259	0.94	T3	IIA
1-Butene	1.6	10.0	-80	455	0.94	T1	IIA
Dekane	0.3	5.6	46	201	1.05	T3	IIA
Dietylether	1.9	36.0	-45	160	0.87	T4	IIB
Dimetylether	3.4	27.0	-42	350	0.84	T2	IIB
Etane	3.0	12.4	?	515	0.91	T1	IIA
Ethanol	3.3	19.0	12	363	0.91	T2	IIA
Ethylene	2.7	36.0	?	425	0.65	T2	IIB
Heptane	1.1	6.7	- 4	215	0.91	T3	IIA
Hexane	1.2	7.4	-21	233	0.93	T3	IIA
Hydrogen	4.0	75.0	?	560	0.28	T1	IIC
Hydrogen sulphide	4.0	44.0	?	270	0.90	T3	IIA
Carbon disulphide	1.3	50.0	-30	102	0.20	T5	IIC
Carbon monoxide	12.5	74.5	?	605	0.84	T1	IIB
Metane	5.0	15.0	?	540	1.14	T1	I/IIA*
Nafta	0.0	6.0	<-18	290	?	T3	IIA
Propane	2.1	9.5	-104	493	0.92	T1	IIA
Styrene	1.1	6.1	30	490	?	T1	IIA
Toluene	1.2	7.1	4	535	?	T1	IIA

* For methane Code I applies to coal mines only, whereas Code IIA applies to all other situations.

a. Data from International Electrotechnical Commission *Data for flammable gases and vapours relating to the use of electrical apparatus.* Committee draft 31 (SEC.) 16Y' made for IEC TC31 by the working group WG4. Central Office of International Electrotechnical Commisssion, Geneva, Switzerland. (1992)

agreement with the conception that an explosive gas (vapor) atmosphere generally cannot exist if the flash point is significantly above the maximum temperature of that fluid.

However, as will be discussed in Chapter 3, if a pressurized combustible liquid at a temperature below its flash points is released to the atmosphere as a spray of small droplets in air, the spray cloud can become ignited and propagate a flame just like a pre-mixed homogeneous explosive gas cloud.

The third column of Table 2–2 gives flash points for some combustible liquids in air. The other four parameters included in Table 2–2 will be discussed later in this chapter in their relevant contexts.

2.1.3.3 Classification of Flammable Fluids According to Their Flash Points

The classification system for flammable fluids recommended by The Institute of Petroleum (2002) is given in Table 2–3. The main classification conforms to the flash point classification systems of the European Directives. The subdivision of Classes II and III has been standardized by The Institute of Petroleum (2002) to aid the handling of petroleum materials throughout bulk storage, loading, conveyance, discharge, and distribution. It should, however, be recognized that there is an upper temperature limit, though unlikely to be encountered, in Classes I, II(2), and III(2) classification applications above which they should not be extended; this upper limit is the temperature at which the liquid would boil.

Table 2–3   Classification of Flammable Fluids According to Their Flash Points[a]

Fluid class	Description
Class 0	Liquefied petroleum gases (LPG)
Class I	Liquids that have flash points below 21 °C
Class II(1)	Liquids that have flash points from 21 °C up to and including 55 °C, handled below flash point
Class II(2)	Liquids that have flash points from 21 °C up to and including 55 °C, handled at or above flash point
Class III(1)	Liquids that have flash points above 55 °C up to and including 100 °C, handled below flash point
Class III(2)	Liquids that have flash points above 55 °C up to and including 100 °C, handled at or above flash point
Unclassified	Liquids that have flash points above 100 °C

a.   *Source*: Data from The Institute of Petroleum *Area classification code for installations handling flammable fluids,* 2d ed. August 2002, The Institute of Petroleum, London.

Typical examples of petroleum fluids are shown in Table 2–4.

Where the flammable fluid is a liquid, its volatility in relation to the conditions of temperature and pressure at which a potential release might take place is an essential factor, since it will determine the extent of rapid vapor formation from that release. In many of the commonly encountered

Table 2-4   Classification of Commonly Encountered Combustible Petroleum Materials[a]

Class of petroleum based on flash point	Examples of petroleum materials	Flash point (°C)	Boiling range (°C)
Class 0	LPGs, ethylene, propylene	Not applicable	Propane - 42 Butane -1 Isobutane -12
Class I <21 °C	Gasoline (petrol) Stabilised crude oil Avtage wide cut jet fuel (JP4; Jet B) Benzene Toluene Naphtha Methanol	-45 <21 -25 -11 4 -2 to 10 11	ca. 20-205 ca. - 1 to 380+ ca. 0-220 80 110 30-177 65
Class II 21-55°C	Avtur/Jet A Turbofuel Kerosine (a) premium grade (b) regular	38 (min.) 43 (min.) 38 (min.)	150-240 160-280 150-280
Class III 55-100 °C	Gas oil/distillate heating oil Automotive diesel fuel	 55+ 55+	 250-360 180-360
Unclassified >100 °C	Atmosphere residues Heavy fuel oils	 >100	 >350

a.   *Source*: Data from The Institute of Petroleum *Area classification code for installations handling flammable fluids*, 2d ed. August 2002, The Institute of Petroleum, London.

types of process plant, the flammable fluid can be classified satisfactorily by its flash point, e.g. in accordance with the procedure of The Institute of Petroleum (2002). Further sub-division of the main classes (II and III) into sub-classes (1) and (2) is done according to whether the liquids are handled at temperatures above or below the flash point.

2.1.4 Maximum Pressures Generated from Constant-Volume Adiabatic Combustion of Premixed Gas/Vapor and Air

If the combustion occurs at constant volume, a pressure rise will result. The adiabatic temperature rise at constant volume can be expressed as

$$T_2 - T_1 = \Delta E / C_v \qquad (2.1)$$

where ΔE is the liberated combustion heat per mole at constant volume, C_v is the mean specific heat of the gaseous system at constant volume, T_1 is the

initial gas mixture temperature (prior to combustion), and T_2 is the final temperature of the combustion products and the nitrogen (from the air) after complete combustion. Ideal T_2 values computed using Equation (2.1) are most often somewhat higher than experimental values, due to inevitable heat losses and non-ideal chemical conversion in real experiments. However, assuming that an adequate T_2 value can be obtained (see Table 2–6), the corresponding constant-volume adiabatic pressure rise can be estimated, using the equation of state (assuming ideal gases)

$$P_2/P_1 = n_2T_2/n_1T_1 \qquad (2.2)$$

where P is pressure (absolute), T is temperature in Kelvins and n is total number of moles of gas in the constant volume considered. A more detailed analysis is given by Kuchta (1985). Table 2–5 and Table 2–6 give some experimental P_2 values. The data in the two tables originate from different sources and deviate somewhat. Different fuel to air ratios in the experiments may be one reason for the discrepancies.

Note that initial temperature T_1 and pressure P_1, deviating from normal atmospheric conditions, will give correspondingly different P_2 values. As

Table 2–5   Highest Maximum Explosion Pressure (Gauge) for Combustion of Premixed Fuel Gas/Air in a Closed 5 Liter Test Vessel[a] [b]

Fuel	bar(g)	Fuel	bar(g)
Acetylene	10.3	i-Butylalcohol	7.6
Ethylene oxide	9.9	Ethyl alcohol	7.5
Bensene	9.0	n-Butylalcohol	7.5
Acetone	8.9	n-Decane	7.5
Ethylene	8.9	Hydrogen	7.4
n-Hexane	8.7	Carbonmonoxide	7.3
n-Pentane	8.7	Methane	7.2
n-Butane	8.6	Toluene	6.8
Cyclohexane	8.6	Vinylchloride	6.8
n-Heptane	8.6	Metylbutadiene	6.6
Propane	8.6	Styrene	6.6
Propylene	8.6	Ammonia	6.0
i-Octane	8.1	Acetic acid	5.4
Carbon disulphide	7.8	Hydrogen sulphide	5.4

a.   The fuel gas/air ratio was varied until the highest explosion pressure had been found for each fuel. Normal atmospheric initial conditions.

b.   *Source:* Data from H.H. Freytag, *Handbuch der Raumexplosionen,* Verlag Chemie, Weinheim, Germany. (1965): 152.

Table 2–6   Combustion Properties of Some Fuel Gas/Air Mixtures. Normal Atmospheric Initial Conditions[a]

Fuel	Vol.% fuel in air	Constant volume	Constant pressure	Adiabatic flame temperature	
		Max. pressure [bar(g)]	Expansion ratio E [-]	Constant volume [K]	Constant pressure [K]
Acetylene	7.75	8.80	8.38	2925	2542
Hydrogen	29.60	7.02	6.88	2755	2384
Ethylene	6.53	8.32	7.48	2740	2372
Butane	3.13	8.43	8.06	2639	2272
Propane	4.0	8.34	7.98	2633	2266
Ethane	5.67	8.21	7.87	2627	2261
Methane	9.51	7.60	7.25	2591	2227

a. *Source*: Data from J.H.S. Lee, *Physics of explosions*, lecture notes, McGill University, Montreal. (1984): 249.

a rule, the maximum adiabatic explosion pressure (absolute) produced by a given fuel/air mixture at constant volume, is proportional to the initial pressure (absolute) prior to combustion. Hence, a gas mixture giving 8 bar (absolute) at atmospheric initial pressure, will yield 16 bar (absolute) at 2 bar (absolute) initial pressure (1 bar overpressure).

In the case of premixed gas explosions in a system of closed volumes in series, coupled via comparatively narrow ducts or pipes, an explosion in one part of the system can give rise to considerable pressure rise in the still unburned gas mixture in other parts (pressure piling). When the flame front reaches and ignites such precompressed gas volumes, very high pressure transients can result, in spite of the fact that the entire system was at atmospheric pressure prior to the first ignition.

2.1.5 The "Expansion Ratio" for Combustion of Premixed Gas/ Vapor and Air

Figure 2–6 illustrates idealized adiabatic (no heat loss to the tube, no buoyancy, no interference of the wall with the gas flow) planar, laminar combustion of premixed quiescent explosive gas/air in a one-end open straight tube/duct, at constant pressure.

If the gas mixture is ignited in a plane across the open end of the tube (Figure 2–6a), the combustion products will expand freely into the ambient atmosphere, whereas the still unburned gas further into the tube will remain
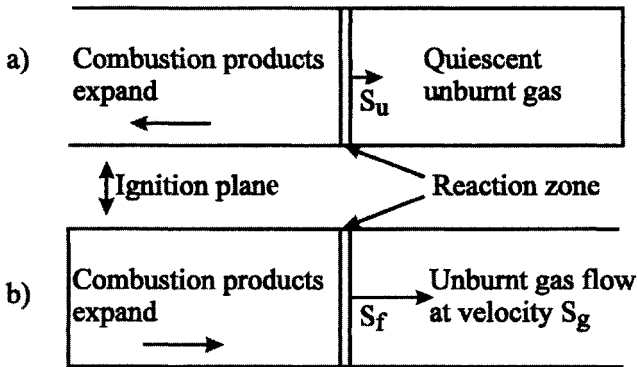
Figure 2–6   Premixed fuel gas/air burning at constant pressure with a plane, laminar flame in a one-end-open tube. a) ignition at open tube end. b) ignition at closed tube end.

quiescent. The observed flame speed in relation to the tube wall will then be identical with the laminar burning velocity S_u of the actual gas/air mixture. If ignition occurs at the closed tube end, however, (Figure 2–6b) the expansion of the combustion products is forced to occur in the same direction as that of flame propagation. Therefore the unburned gas mixture ahead of the flame will be pushed towards the open tube end. In this case the observed flame speed S_f in relation to the tube wall is the sum of S_u and the flow velocity S_g of the unburned gas. Hence, Equation (2.3) and Equation (2.4) describe how the liberated combustion heat, in the case of constant pressure, gives rise to expansion.

$$S_f = S_u + S_g \tag{2.3}$$

or

$$S_f = S_u \cdot E \tag{2.4}$$

Here E is the "expansion ratio", simply defined by Equation (2.4) as S_f/S_u, or by using Equation (2.3), as $(1 + S_g/S_u)$.

In other words, E is the ratio of the volume that a given quantity of premixed gas has attained after complete, ideal adiabatic combustion at constant pressure, and its volume before combustion. For a given fuel, E

varies with the fuel/air ratio and has its maximum around the stoichio-
metric ratio or somewhat higher. Maximum E values for most hydrocar-
bons in air are in the range 7.5–8.0. Some values are given in Table 2–6.
The reason for this substantial expansion is the large amount of heat liber-
ated when the fuel and oxygen combine and form combustion products
(CO_2 and H_2O for complete combustion of hydrocarbons). Note that the
term *burning velocity* is by definition the relative linear velocity S_u by
which the combustion reaction is "eating" itself into the unburned gas/air
mixture, whereas *flame speed* denotes the linear velocity S_f of the flame
front in relation to a stagnant observer or structure or apparatus. If the
combustion occurs under conditions where expansion cannot occur freely,
the liberated heat may give rise to a substantial pressure rise, which, in
turn, may cause substantial damage to industrial equipment, plants, build-
ings etc. (see Table 2–5 and Table 2–6).

Figure 2–7 illustrates ideal laminar spherical combustion of a premixed
gas/air cloud, following ignition at a point in the cloud. In this case,
assuming a very thin flame and negligible buoyancy, the unburned gas/air
will always be pushed in the direction of flame propagation, and
Equation (2.3) and Equation (2.4), with the same numerical values as for
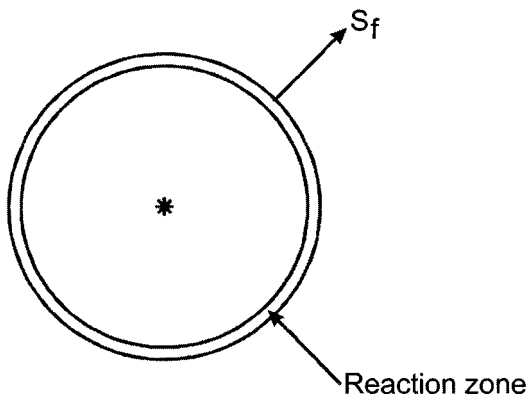the linear case in Figure 2–6b, apply even in this case.

**Figure 2–7   Ideal laminar spherical burning of quiescent premixed fuel gas/air,
following ignition at a point.**

2.1.6 Turbulent Combustion of Premixed Gas/Vapor and Air

In real premixed accidental explosions of gas clouds in an industrial plant, the cloud will not be quiescent but turbulent. Flame propagation in turbulent gas is illustrated in Figure 2–8.
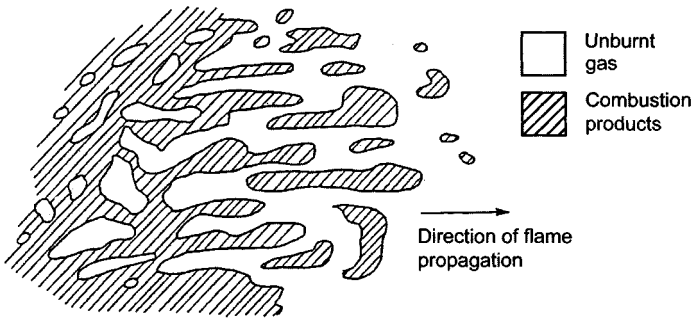

Figure 2–8   Illustration of flame front structure in turbulent premixed gas.

In this case the flame front is no longer a continuous, plane sheet, but folded and torn, with an effective surface area that can be substantially larger than the nominal projected area. This in turn gives rise to nominal turbulent burning velocities that can be considerably higher than the laminar value for the gas mixture in question. Figure 2–9 gives some results from measurements in a burner similar to the one illustrated in Figure 2–2.

When discussing accidental gas explosions one distinguishes between two kinds of turbulence, initial or pre-explosion turbulence, and turbulence generated by the explosion itself. The latter is caused by the transient flow of the unburned gas ahead of the flame, generated by the expansion of the combustion products behind the flame. The production of this kind of turbulence is particularly exaggerated in areas packed with process equipment, pipes and other kinds of obstructions to the flow, as illustrated in Figure 2–69.

Figure 2–10 illustrates the dramatic effects that can result from gas explosions in obstructed geometries.

These experiments were performed in a one-end-open tube of diameter 2.5 m, length 10 m and volume 50 m^3. Ring-shaped turbulence-generating steel baffles could be mounted at various positions in the tube. Because the tube was fully open at one end, the rate of combustion had to be very
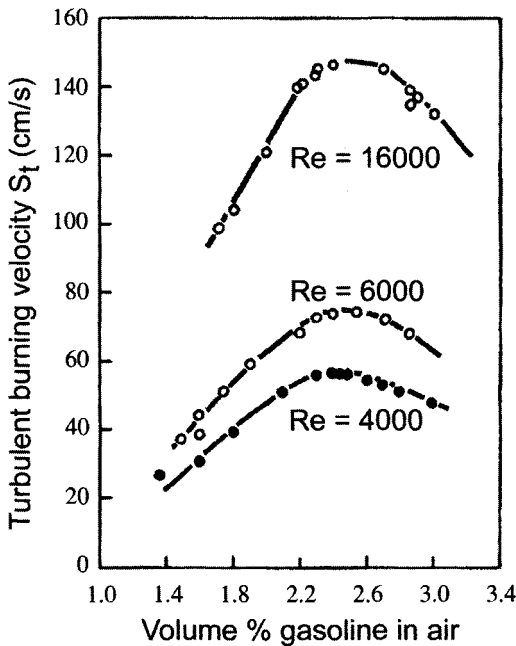
Figure 2–9   Turbulent burning velocity as a function of Reynolds number Re. Premixed gasoline/air in steady-state burner of diameter 16 mm. From Freytag (1965) p. 70.

high for high explosion overpressures to be generated inside the tube. As the table in Figure 2–10 shows, the influence of introducing the flow obstructing rings on the maximum explosion overpressure in the tube was dramatic, no rings giving 0.15 bar(g), 1 ring 0.6 bar(g), 3 rings 3.5 bar(g), and 6 rings 8.0 bar(g). In other words, the variations in overpressure were by more than a factor of 50! These experiments urged the development of the computer code FLACS that can predict the explosion overpressures to be expected from a given fuel gas/air system, as a function of geometry of the explosion environment, and the location of the ignition point (see Section 2.4.5.7).

2.1.7 Detonation of Premixed Gas/Vapor and Air

Detonation is an extreme singular mode of flame propagation in premixed gas. In this mode the combustion zone follows immediately behind, and
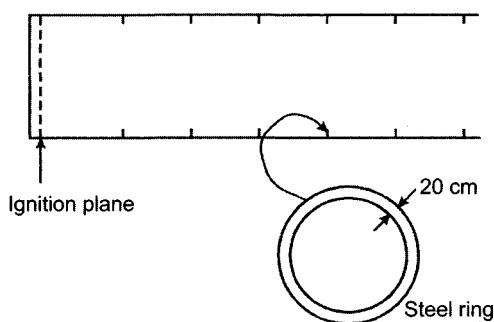
Max explosion pressures in tube for 9.5 vol. % methane in air	
Ring configuration	[bar(g)]
No ring in tube	0.15
1 ring 2 m from ign.plane	0.60
3 rings	3.50
6 rings (as shown in fig.)	8.00

Figure 2–10   Experiment performed in Norway to determine the influence of explosion-generated turbulence on the violence of gas explosions, using turbulence-generating rings (baffles). From Moen et al. (1982).

drives, a leading shock front moving into the quiescent, unburned gas mixture at supersonic velocity. The mechanism of flame propagation is then no longer thermal diffusion, but extremely rapid compression, whereby the temperature in the compression zone is raised to such a high level that ignition occurs almost instantaneously. The necessary condition for self-sustained detonation propagation is that the shock wave is sufficiently strong for the volume inside it to become ignited and react chemically before the shock wave has traveled a significant distance away. In this way the shock wave and the chemical reaction zone remain closely coupled, and the shock wave speed and strength is maintained. As shown in Table 2–7, typical detonation velocities in premixed hydrocarbon gas/air, at normal initial pressure and temperature and optimum fuel concentrations, are 1800–1900 m/s, i.e. of the order of five times the velocity of sound in the unburned, uncompressed premixed gas/air. For this reason, the unburned mixture ahead of the detonation front cannot receive any gas dynamic signal from the approaching detonation front until being caught

Table 2-7   Detonation Properties of Some Fuel Gases Premixed with Air at Atmospheric Pressure and Temperature— Stoichiometric Mixtures[a]

Fuel	Detonation velocity [m/s]	Overpressure in detonation front [bar(g)]
Methane	1800	16.1
Ethane	1800	17.0
Propane	1800	17.3
Butane	1800	17.4
Ethylene	1860	17.7
Acetylene	1870	18.0
Hydrogen	1960	14.6

a.   *Source:* Data from J.H.S Lee, *Physics of explosions.* Lecture notes, McGill University, Montreal. (1984): 249.

by the front itself. Therefore, reducing the maximum explosion pressure of a detonation by explosion venting is impossible.

Detonations can be initiated directly by means of a sufficiently strong explosive charge or electric spark. In accidental explosions in industry, Deflagration-to-Detonation Transition (DDT) is the common initiation mechanism. This can occur in long ducts, when turbulence and burning rates increase to such high levels that the compressed unburned gas, trapped between the flame front and the leading shock, ignites spontaneously. Extremely high transient pressure peaks can then be generated before stable detonation conditions are attained.

In addition to typical detonation front velocities, Table 2–7 also gives corresponding detonation peak pressures. Hydrogen deviates from the hydrocarbons because the density of 30% hydrogen in air is only 18/29 of the density of air, and the velocity of sound therefore 418 m/s as opposed to 330 m/s (C_1 in Equation (2.5)).

Figure 2–11 shows the result of an experiment in which stoichiometric premixed acetylene/air detonated in a 46 m long tube of diameter 0.6 m.

Some simple relations are useful. The first is

$$P_{CJ}/P_1 = [1 + \gamma_1(V^*/C_1)^2]/[1 + \gamma_2] \qquad (2.5)$$

where P_{CJ} is the Chapman-Jouguet detonation front pressure, P_1 the initial pre-ignition pressure, γ_1 and γ_2 the C_p/C_v ratio (specific heats at constant pressure and volume) for the pre-ignition gas mixture and the combustion
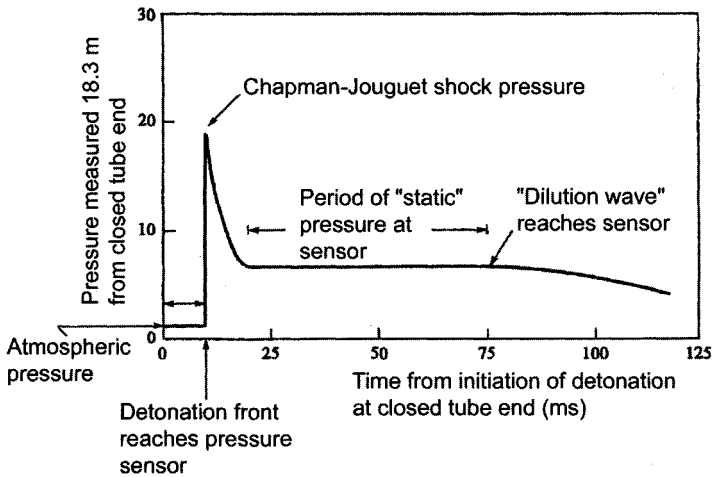
Figure 2–11   Detonation of a stoichiometric mixture of acetylene and air in a one-end-open tube of diameter 0.6 m. The detonation was initiated at the closed tube end by means of an explosive charge. The pressure sensor was located 18.3 m from the closed tube end. From Kuchta (1985) p. 18.

products respectively, V* the detonation front velocity in the unburned mixture, and C_1 the velocity of sound in the pre-ignition mixture. $V*/C_1$ is the Mach-number, which is $>>1$ for detonation fronts in hydrocarbon/air mixtures.

The following rule of thumb gives useful guidance:

$$P_{CJ} \approx 2P_2 \qquad (2.6)$$

where P_2 is the maximum adiabatic explosion pressure at constant volume (Table 2–5 and Table 2–6).

For any given ideal gas the velocity of sound C is independent of pressure, but dependent on temperature. The following relation applies:

$$C = [(\gamma P_o T)/(273 \rho_o)]^2 \qquad (2.7)$$

where γ is C_p/C_v (≈ 1.4 for 2-atomic gases), P_o and ρ_o the gas pressure and density at the same reference temperature, and T is the absolute temperature of the gas. In other words, at any given T, the velocity of sound C is inversely proportional to $M^{0.5}$, where M is the mole weight of the gas.

For this reason, C at any given temperature is considerably higher in hydrogen than in air.

Figure 2–12 illustrates the dramatic span (logarithmic scale) of possible burning velocities of a given fuel/air mixture, using propane/air as an example. The concentration ranges for detonation are somewhat narrower than for turbulent combustion, which are in turn somewhat narrower than that for laminar burning. Table 2–8 gives some figures illustrating this.

Table 2–8   Comparison of Composition Limits for Laminar Burning and Detonation for Two Combustible Gases Mixed with Air[a]

Fuel	Limits for laminar flames [vol.% in air]		Detonability limits* [vol.% in air]	
	Lower	**Upper**	**Lower**	**Upper**
Acetylene	2.5	100	4.2	50
Hydrogen	4.0	75	18.3	59

a.   *Source*: Data from Table 2–2 and H. H. Freytag, *Handbuch der Raumexplosionen*. Verlag Chemie, Weinheim, Germany. (1965): 74.

2.2 Ignition of Premixed Gas/Vapor and Air

2.2.1 Introduction

This section concentrates mainly on initial cloud conditions of normal atmospheric pressure and temperature, and on ignition of pre-mixed hydrocarbon gases and air. Experimental evidence elucidating the basic features of various ignition processes and practical guidelines for prevention of ignition in industrial process plants are considered.

The phrase *ignition source* is used as a general term embracing all categories of heat source that may, in principle, give rise to ignition. The phrase *effective ignition source* indicates that a particular source will actually cause ignition if brought into contact with the specific explosive atmosphere of concern.

Numerous national and international standards and guidelines are currently in place for preventing accidental ignition of explosive atmospheres. In Europe, a comprehensive standard was drafted by CEN