

NFPA®

67

**Guide on Explosion
Protection for Gaseous
Mixtures in Pipe Systems**

2019



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NFPA® 67

Guide on

Explosion Protection for Gaseous Mixtures in Pipe Systems

2019 Edition

This edition of NFPA 67, *Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems*, was prepared by the Technical Committee on Explosion Protection Systems. It was issued by the Standards Council on November 5, 2018, with an effective date of November 25, 2018, and supersedes all previous editions.

This edition of NFPA 67 was approved as an American National Standard on November 25, 2018.

Origin and Development of NFPA 67

In 1965, an NFPA committee was appointed to develop standards for explosion protection systems. The standards were to include information on explosion prevention and mitigation in vessels, ducts, and buildings, focusing primarily on deflagrations. During a meeting in 1997, the committee first considered the subject of protection against detonations in manifold pipe networks out of concern for the proliferation of vapor recovery systems at flammable liquid transfer stations. In 1999, the Standards Council approved the creation of a new document to address this issue, and the first draft of NFPA 67 was presented in 2011. Following a period of public review and comment, NFPA 67, *Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems*, was issued in 2013.

The 2016 edition expanded the section on detonation forces on pipes, provided additional guidance on the proper application of detonation arresters, and provided references to address the design of piping systems that are outside the scope of this guide.

The 2019 edition includes three additional applications where NFPA 67 can be applied where there is potential for flammable gas formation. A new annex has been added to provide examples of applying the equations for suitable pipe wall thickness for pipe wall elastic response to stable detonations. Additional clarifications were made throughout the guide to assist the user.

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Committee Scope: This Committee shall have primary responsibility for documents on explosion protection systems for all types of equipment and for buildings, except pressure venting devices designed to protect against overpressure of vessels such as those containing flammable liquids, liquefied gases, and compressed gases under fire exposure conditions, as now covered in existing NFPA standards.

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2019 Edition

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

A reference in brackets [] following a section or paragraph indicates material that has been extracted from another NFPA document. As an aid to the user, the complete title and edition of the source documents for extracts in mandatory sections of the document are given in Chapter 2 and those for extracts in informational sections are given in Annex C. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text shall be sent to the technical committee responsible for the source document.

Information on referenced publications can be found in Chapter 2 and Annex C.

Chapter 1 Administration

1.1 Scope.

1.1.1 This guide applies to the design, installation, and operation of piping systems containing flammable gases where there is a potential for ignition.

1.1.2 This guide addresses protection methods for use where the pipe explosion risk is due to either a deflagration or a detonation.

1.1.3 This guide does not apply to runaway reactions, decompositions, or oxidants other than oxygen.

1.2 Purpose. The purpose of this guide is to provide the user with criteria for designing piping systems to protect against damage from deflagrations or detonations due to combustion

of flammable atmospheres therein. Protection of a pipe system can be by application of explosion prevention methods (see NFPA 69), deflagration venting (see NFPA 68), passive or active suppression and isolation methods, or containment. Deflagration containment or deflagration venting should include layout or designs that minimize the probability of deflagration-to-detonation transition (DDT), unless the nonventing components of the system are designed to contain detonation.

1.3 Piping Installation and Maintenance. Installation of piping systems addressed in this guide should be designed in accordance with applicable standards, such as NFPA 54, ASME B31.1, ASME B31.3, or ASME B31.12.

1.3.1 There are additional standards, such as NFPA 2, NFPA 55, and NFPA 58, that also include requirements for specific gases and applications.

1.3.2 Inadvertent formation of flammable gas mixtures during pipe cleaning and purging can be prevented by following the planning and procedures described in NFPA 56.

1.4 Applications. Applications of this guide include the following:

- (1) Process piping for which a hazard analysis has identified the potential for flammable mixtures
- (2) Vapor recovery system piping
- (3) Gas venting piping and manifolds
- (4) Gas piping for water electrolysis and fuel cell systems
- (5) Flare systems
- (6) Fuel gas piping for which a hazard analysis has identified the potential for flammable mixtures
- (7) Oxygen piping for which there is a potential for flammable gas or vapor entry
- (8) Piping cleaned by flammable liquid solvents that can develop flammable mixtures

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this guide and should be considered part of the recommendations of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 2, *Hydrogen Technologies Code*, 2016 edition.

NFPA 54, *National Fuel Gas Code*, 2018 edition.

NFPA 55, *Compressed Gases and Cryogenic Fluids Code*, 2016 edition.

NFPA 56, *Standard for Fire and Explosion Prevention During Cleaning and Purging of Flammable Gas Piping Systems*, 2017 edition.

NFPA 58, *Liquefied Petroleum Gas Code*, 2017 edition.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, 2018 edition.

NFPA 69, *Standard on Explosion Prevention Systems*, 2019 edition.

2.3 Other Publications.

2.3.1 API Publications. American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070.

API STD 2000, *Venting Atmospheric and Low-Pressure Storage Tanks*, 2014.

2.3.2 ASME Publications. American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990.

ASME B31.1, *Power Piping Code*, 2016.

ASME B31.3, *Process Piping Code*, 2016.

ASME B31.12, *Hydrogen Piping and Pipelines Code*, 2014.

2.3.3 ASTM Publications. ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

ASTM E681, *Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)*, 2009, reapproved 2015.

ASTM E2079, *Standard Test Method for Limiting Oxygen (Oxidant) Concentration in Gases and Vapors*, 2007, reapproved 2013.

2.3.4 ISO Publications. International Organization for Standardization, ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland.

ISO 16852, *Flame arresters — requirements, test methods and limits for use*, 2016 edition.

ISO 28300, *Petroleum, petrochemical and natural gas industries — Venting of atmospheric and low-pressure storage tanks*, 2008.

2.3.5 U.S. Government Publications. U.S. Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401-0001.

Title 29, Code of Federal Regulations, Part 1910.146, "Permit-Required Confined Spaces"

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Zhou, B., A. Sobiesiak, and P. Quan, "Flame Behavior and Flame-Induced Flow in a Closed Rectangular Duct with a 90° Bend," *International Journal of Thermal Sciences* 45 (2006): 457–474.

2.4 References for Extracts in Advisory Sections.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, 2018 edition.

NFPA 69, *Standard on Explosion Prevention Systems*, 2019 edition.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter apply to the terms used in this guide. Where terms are not defined in this chapter or within another chapter, they should be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster's Collegiate Dictionary*, 11th edition, is the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Authority Having Jurisdiction (AHJ). An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

3.2.3 Guide. A document that is advisory or informative in nature and that contains only nonmandatory provisions. A guide may contain mandatory statements such as when a guide can be used, but the document as a whole is not suitable for adoption into law.

3.2.4 Labeled. Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials, and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

3.2.5* Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

3.2.6 Should. Indicates a recommendation or that which is advised but not required.

3.3 General Definitions.

3.3.1 Burning Velocity (S_u). The rate of flame propagation relative to the velocity of the unburned gas that is ahead of it. [68, 2018]

3.3.1.1 Fundamental Burning Velocity. The burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. [68, 2018]

3.3.2 Combustion. A chemical process of oxidation that occurs at a rate that is fast enough to produce heat and usually light, in the form of either a glow or flames.

3.3.3 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.

3.3.4 Deflagration-to-Detonation Transition (DDT). The transition point to an unstable detonation.

3.3.5* Detonation. Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium.

3.3.6 Detonation Cell Size. (Reserved)

3.3.7 Dynamic Load Factor (DLF). The ratio of the deformation in a detonation to the deformation expected for a static load based on the Chapman-Jouguet detonation pressure (*see Equation 7.7.1.1*).

3.3.8 Equivalence Ratio. For a particular fuel-oxidant mixture, the fuel oxidant ratio of a particular mixture divided by the fuel oxidant ratio of the stoichiometric mixture.

3.3.9* Flame Arrester. A device that prevents the transmission of a flame through a flammable gas/air mixture by quenching the flame on the surfaces of an array of small passages through which the flame must pass. [69, 2019]

3.3.10 Flame Speed (S_f). The speed of a flame front relative to a fixed reference point.

3.3.11 Flammable Limits. The minimum and maximum concentrations of a combustible material, in a homogeneous mixture with a gaseous oxidizer, that will propagate a flame.

3.3.12 Flammable Mixture. A mixture of fuel, oxygen (or other oxidant), and inert gases that has a composition in the flammable range.

3.3.13 Flammable Range. The range of concentrations between the lower and upper flammable limits.

3.3.14 Flash Point. The minimum temperature at which a liquid gives off vapor in sufficient concentration to form an ignitable mixture with air near the surface of the liquid, as specified by test.

3.3.15 Fuel. A material that will maintain combustion under specified environmental conditions.

3.3.16 Gas. The state of matter characterized by complete molecular mobility and unlimited expansion; used synonymously with the term *vapor*.

3.3.17 Limiting Oxidant Concentration (LOC). The concentration of oxidant in a fuel-oxidant-diluent mixture below which a deflagration cannot occur under specified conditions.

3.3.18 Lower Flammable Limit (LFL). The lowest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame, under defined test conditions.

3.3.19 Mach Number (M). The velocity divided by the local speed of sound. The Mach number of a propagating flame front is the flame speed divided by the speed of sound in the unburned mixture.

3.3.20 Maximum Pressure (P_{max}). The maximum pressure developed in a contained deflagration of an optimum mixture.

3.3.21 Maximum Rate of Pressure Rise (dP/dt_{max}). The slope of the steepest part of the pressure-versus-time curve recorded during deflagration in a closed vessel.

3.3.22 Minimum Ignition Energy (MIE). The minimum amount of energy released at a point in a combustible mixture that causes flame propagation away from the point, under specified test conditions.

3.3.23 Mist. A dispersion of fine liquid droplets in a gaseous medium.

3.3.24* Optimum Mixture. A specific mixture of fuel and oxidant that yields the most rapid combustion at a specific measured quantity or that yields the lowest value of the minimum ignition energy or that produces the maximum deflagration pressure.

3.3.25 Oxidant. Any gaseous material that can react with a fuel (gas, dust, or mist) to produce combustion.

3.3.26 Pressure Piling. A condition during deflagration in which pressure increases in the unreacted medium ahead of the propagating combustion zone.

3.3.27 Rate of Pressure Rise (dP/dt). The increase in pressure divided by the time interval necessary for that increase to occur.

3.3.28 Reduced Pressure (P_{red}). The maximum pressure developed in an enclosure during a mitigated deflagration.

3.3.29 Static Activation Pressure (P_{stat}). Pressure that activates a vent closure when the pressure is increased slowly (with a rate of pressure rise less than 0.1 bar/min).

3.3.30 Stoichiometric Mixture. A balanced mixture of fuel and oxidizer such that no excess of either remains after combustion.

3.3.31 Ultimate Strength. The pressure that results in the failure of the weakest component of an enclosure.

3.3.32 Upper Flammable Limit (UFL). The highest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame.

3.3.33 Vapor. See 3.3.16, Gas.

3.3.34 Vent. An opening in the enclosure to relieve the developing pressure from a deflagration.

Chapter 4 Fundamentals of Deflagrations

4.1* General. A deflagration is the propagation of a combustion flame front through a flammable atmosphere at a velocity that is less than the speed of sound in the unreacted medium. The rate of propagation of a deflagration is controlled by diffusion of heat and reactive species from the reaction zone (flame front) to the unburned material. In practice, the flame propagation velocity depends on the degree of confinement and the size and shape of the flammable mixture. Assuming that the unburned gas is stationary, the flame propagates into the unburned gas at a characteristic laminar burning velocity. This is a fundamental parameter whose value reflects the reactivity of the mixture. If the unburned gas is turbulent, the burning velocity can increase and is then called the turbulent burning velocity. If the unburned gas is moving, a stationary observer measures a flame velocity that is the sum of the unburned gas velocity and the burning velocity. This observed flame speed is called the deflagration velocity. Typical deflagration speeds range from a few meters per second in an unconfined cloud to several hundreds of meters per second in a pipe or other

volume containing repeated obstacles. In an enclosed vessel containing a fuel-air mixture, the deflagration pressure rise is typically seven to nine times the initial pressure.

4.1.1 Example and Explanation of Limitations. (Reserved)

4.2* Flammable Limits. A flammable gas mixture is one consisting of fuel, oxygen, and inert gases that can propagate a flame. *Flammable limits* usually refers to the lowest and highest concentrations of fuel vapor in atmospheric air that will propagate a flame. Determination of flammable limits is by test such as ASTM E681 or ASTM E2079. Examples of flammable limits for several gases are given in Table 4.2.

▲ Table 4.2 Flammable Limits in Air

Fuel	LFL (Vol. %)	UFL (Vol. %)
Methane	5.3	15
Ethane	3.0	12.5
Propane	2.2	9.5
Butane	1.8	8.4
Ethylene	3.1	32
Methyl alcohol	7.3	36
Hydrogen	4.0	75
Acetone	3.0	13
Methyl acetate	3.1	16

4.3 Burning Velocity.

4.3.1 General. Burning velocity (also called fundamental burning velocity) is the rate of flame propagation relative to the velocity of the unburned gas that is ahead of the reaction zone or flame front. A flame front propagates by heat transfer, conduction, and radiation from the reaction zone to adjacent unburned gas. Many different elementary reactions result in the global chemical process called combustion. The rates of these reactions in a volume of heated gas increase with temperature (approximately exponentially), eventually reaching the point of becoming self-sustaining. The self-sustaining point of combustion is that at which a volume of flammable mixture generates more thermal energy than it loses, with the effect that the local temperature rises rapidly to the final flame temperature. Burning velocity is a reactivity characteristic of a flammable gas that depends on fuel type, fuel composition (χ) in the fuel-air (or other oxidant) mixture, initial temperature, and pressure. The burning velocity is designated S_b .

4.3.2 Maximum Burning Velocity. The burning velocity of a given fuel in air will have a maximum value in the composition domain, typically in a region that is somewhat fuel rich. Values of the maximum burning velocity for a number of flammable gases are given in Table 4.3.2.

4.3.3 Determination of Burning Velocity. Burning velocity can be determined by test, and several methods have been used, including those based on size measurement of Bunsen flames and pressure development in closed vessels.

4.4 Flame Speed. The speed of a flame front, S_b , measured in relation to a fixed special reference frame, is the sum of the burning velocity, S_u , and the flow velocity induced in the unburned gas by the rate of production of combustion products, S_p , as follows:

▲ Table 4.3.2 Maximum Burning Velocity of Selected Flammable Gases in Air

Fuel	Maximum S_u (cm/s)
Acetone	54
Acetylene	166
Acrylonitrile	50
Butane	45
Carbon disulfide	58
Carbon monoxide	46
Decane	43
Dimethyl ether	54
Ethane	47
Ethylene	80
Ethylene oxide	108
Hydrogen	312
Isopropyl alcohol	41
HFC-152a	23.6
HFC-143a	7.1
HFC-32	6.7
HFC-143	13.1
Methane	40
Methyl alcohol	56
Propane	46
Propylene oxide	82
Toluene	41

HFC-32: difluoromethane; HFC-143: 1,1,2-trifluoroethane;

HFC-143a: 1,1,1-trifluoroethane; HFC-152a: 1,1-difluoroethane.

Note: Abstracted from NFPA 68, Table D.1.

[4.4]

$$S_F = S_u + S_p$$

4.4.1 In the simplest case, the volumetric rate of production of combustion products is equal to the total area of the flame front times the burning velocity at the conditions (temperature and pressure) of the unburned gas, as follows, where Q_p is the integral of the composition-dependent burning velocity, $S_u(\chi)$, over the flame surface, s_{FF} .

[4.4.1]

$$Q_p = \int S_u(\chi) \cdot ds_{FF}$$

4.4.2 The component of flow velocity induced by the production of combustion products is as follows, where A is the cross-sectional area of flow:

[4.4.2]

$$S_p = \frac{Q_p}{A}$$

4.4.3 In a closed system, such as a duct, the flame speed is time, space, and composition dependent. Flame speed increases with passage in a smooth duct due to flame stretch from wall friction. Any feature in a duct, such as an obstacle in the flow path, that causes the flame surface area to become extended will lead to acceleration of the flame front.

4.5 Mixtures.

4.5.1 General. Mixtures of fuel gases can result in deflagration properties that are different from those of the original individual fuel gas species. The combination of fuel gas species can also result in unforeseen chemical or molecular transport interaction between fuels. Experimental determination of deflagration parameters of fuel mixtures is recommended. Properties of fuel mixtures can be approximated using simplified mixing formulas, based on the mixture composition and properties of the component fuel gases.

4.5.2 Lower Flammable Limits of Mixtures. The lower flammability limit (LFL) of a mixture of fuels can be approximated using Le Chatelier's mixing rule, based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

$$(LFL)_{mixture} = \frac{1}{\sum \frac{x_i}{(LFL)_i}} \quad [4.5.2]$$

4.5.3 Burning Velocities of Mixtures. The fundamental burning velocity of gas mixtures can be approximated using a Le Chatelier-type mixing rule, based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

$$(S_u)_{mixture} = \frac{1}{\sum \frac{x_i}{(S_u)_i}} \quad [4.5.3]$$

4.5.4 Maximum Adiabatic Flame Temperature and Pressure of Mixtures. The maximum adiabatic flame temperature and pressure achieved by a fuel mixture in a closed vessel or at atmospheric pressure can be calculated using an equilibrium composition software program, such as NASA's Chemical Equilibrium with Applications (CEA) program, or similar thermodynamic model. Using this software, the final pressure and temperature of the gas mixture is obtained for a known initial composition, temperature, and pressure, assuming a constant internal energy and density. The maximum temperature and pressure calculated in this manner will be greater than values obtained in closed vessel experiments, due to heat losses at the vessel boundary during experiments.

Chapter 5 Principles of Detonations

5.1 Properties.

5.1.1 Detonations require fuel-oxidant mixtures that are sufficiently reactive for the combustion zone to propagate at supersonic speeds, that is, to keep pace with the leading shock wave. The shock wave heats the reactive mixture and triggers a rapid combustion reaction with its associated exothermic energy release. The maximum pressure and temperature exist at the reaction front, and there is a continuous decrease of pressure and temperature behind the flame. Pressure loads produced by detonations are described in Chapter 6.

5.1.2 Because the maximum pressure in a detonation occurs as a shock wave, there is no opportunity to detect the rising pressure and take post-ignition mitigating action, as in a deflagration. The primary detonation protection measures are prevention, as discussed in this chapter, and containment, as discussed in Chapter 6. There are also a few possible mitigation measures to arrest or weaken the propagating detonation, as described in Chapter 8, but those measures must be in place before the detonation occurs.

5.1.3 An inherent property of propagating detonations is the occurrence of transverse waves with complicated three-dimensional structures. These transverse waves produce geometric cellular patterns that can be captured optically or by impressions on smoke foils lining the inner surface of detonation tubes. The size of the detonation cells is related to the combustion kinetics, such that faster-burning gas mixtures have smaller detonation cells than slow-burning mixtures. The detonation cell size is also a key parameter in the criteria for detonation composition limits in a particular piping configuration.

5.1.4 Detonation cell size data for a variety of gas-air mixtures are plotted in Figure 5.1.4 as a function of mixture equivalence ratio. The solid curves in Figure 5.1.4 are based on chemical reactivity calculations that produce a reaction scale length, ℓ , which is multiplied by an empirical coefficient, A .

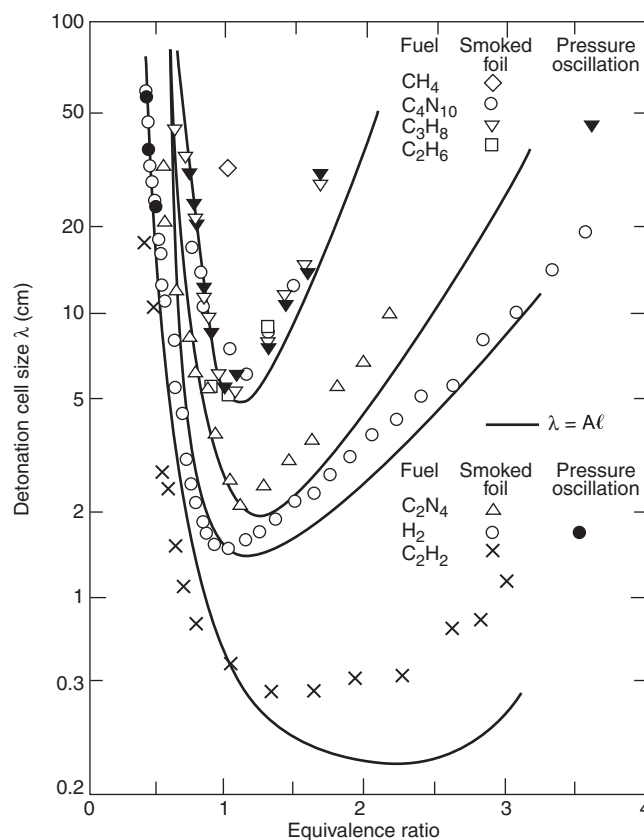


FIGURE 5.1.4 Detonation Cell Size Versus Fuel-Oxygen Equivalence Ratio.

5.2 Detonation Cells and Mixture Composition Limits.

5.2.1 Extensive research over the past 30 years has demonstrated that composition limits for detonation propagation are scale dependent, with the governing parameter being the ratio of the pipe diameter (or other characteristic equipment dimension) to the detonation cell size.

5.2.2 The minimum tube or pipe diameter in which a detonation can propagate, also termed the critical diameter, is equal to λ/π , where λ is the detonation cell size for a particular gas mixture at a specified temperature and pressure.

5.2.3 Gas-air lower and upper composition limits for detonations in pipes with diameters of 25 mm (1 in.), 50 mm (2 in.), and 100 mm (4 in.) are shown in Table 5.2.3 for acetylene-air, ethylene-air, hydrogen-air, methane-air, and propane-air mixtures initially at 1 atmosphere and 300 K. Except for methane (which cannot detonate in pipe diameters smaller than 100 mm), the detonation limits for the gases widen as the pipe diameter increases. If gas composition is outside the range of upper and lower detonation limits, the mixture would not be expected to detonate in an internally smooth pipe of the indicated or smaller diameter.

5.2.4 Detonation limits for the gases listed in Table 5.2.3 in pipes with other diameters in the range 25 mm to 100 mm can be determined via linear interpolation of the data in Table 5.2.3.

5.2.5 Detonation limits for other alkane-air gas mixtures can be estimated from the cell size data in Figure 5.1.4 for ethane, propane, and butane.

Table 5.2.3 Detonation Limits for Gas-Air Mixtures at 300 K and 1 Atmosphere

Pipe Inner Diameter (mm)	Gas	Lower Limit for Detonation (vol. %)	Upper Limit for Detonation (vol. %)
25	Acetylene	4	No data
	Ethylene	4.7	12.3
	Hydrogen	19	58
	Methane	NA	NA
	Propane	3.3	5.4
50	Acetylene	3.4	No data
	Ethylene	4	14.9
	Hydrogen	17	59
	Methane	NA	NA
	Propane	3.1	6.3
100	Acetylene	3.1	No data
	Ethylene	3.4	17.4
	Hydrogen	15	61
	Methane	9.5	9.5
	Propane	2.9	7.5

NA: Stable detonations are not possible for methane in this diameter pipe.

Note: Entries for acetylene, ethylene, methane, and propane were calculated from the data in Figure 5.1.4. Data for hydrogen were obtained from Appendix D of the OECD Nuclear Energy Agency State of the Art Report.

5.2.6 In channels or ducts with small height/width ratios, the minimum channel height that can support a detonation of a particular gas mixture is equal to one detonation cell size and can be estimated using the detonation cell size data in Figure 5.1.4.

5.2.7 In an external cloud of a heavier-than-air flammable mixture, the minimum cloud height that can support a detonation is equal to 1.5 times the detonation cell size shown in Figure 5.1.4.

5.3 Chapman-Jouguet (CJ) Detonations.

5.3.1 Each flammable gas mixture, at a given temperature and pressure, has a unique detonation velocity for which the corresponding velocity of the burned gases is equal to the speed of sound in the burned gases. This unique velocity is called the Chapman-Jouguet (CJ) detonation velocity.

5.3.2* The CJ detonation velocity and the associated detonation pressure and temperature can be calculated from a combination of thermochemical equilibrium constraints and shock wave discontinuity conservation equations. Several computer codes are available to do those calculations.

5.3.3 Extensive experiments have shown that detonations in pipes and tubes tend toward CJ velocities and pressures, and will eventually propagate as CJ detonations if the pipe or tube lengths and diameters are sufficiently large.

5.3.4 CJ detonation pressures for an assortment of flammable gas-air mixtures are shown in Figure 5.3.4. Near-stoichiometric mixtures have CJ detonation pressures in the range 16 to 20 bar. These values are approximately twice the corresponding values of $P_{\max}$ for deflagrations of those gas mixtures.

5.3.5 Chapman-Jouguet detonation velocities and pressures for ethylene-air mixtures are shown in Figure 5.3.5. The near-limit mixture detonation velocities are about 1500 m/s, while the near-stoichiometric mixture detonation velocities are about 1900 m/s.

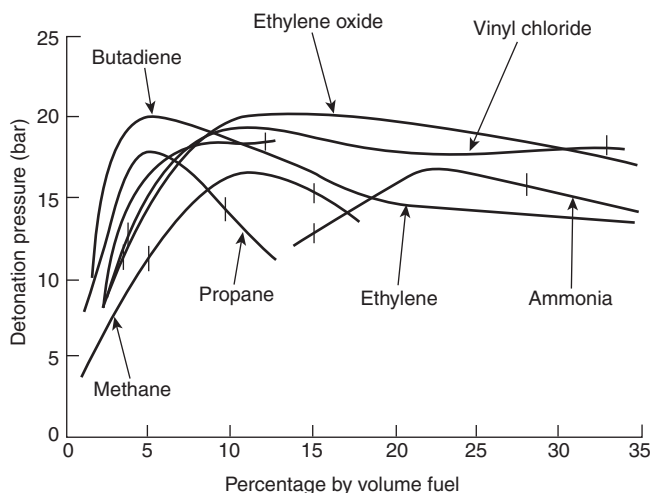


FIGURE 5.3.4 Chapman-Jouguet Detonation Pressures as a Function of Fuel Concentration for Various Flammable Gas-Air Mixtures.

5.4 Detonation Development from Deflagration.

5.4.1 Flame Acceleration in a One-Dimensional System. The initiation of a detonation in a tube closed at one end can be explained by a simplified one-dimensional model as shown in Figure 5.4.1. This model does not consider that local “explosions” can generate oblique pressure waves. After ignition, the flame propagates. The unburned gas is driven to the open tube end, and the processes described above start growth of the flame front, beginning of turbulence, and increasing compression of unburned and burned gas, which can lead to shock waves. With increasing compression, the location at which self-ignition is possible after heating of the fresh gas by shock waves moves closer to the flame, into the flame, and finally ahead of the flame. Hence, after self-ignition, the gas reacts before it is reached by the flame. This generally leads to an increase in the shock-wave intensity, and a backward-running pressure wave (retonation wave) appears. The propagation mechanism of the combustion process changes once a shock wave forms. While transport processes in a flame co-determine the flame velocity and its propagation velocity, they play practically no role in ignition by shock waves. The pressure that is reached at the point of transition to a detonation is generally much higher, sometimes several times higher, than the CJ pressure of the corresponding detonation. In Figure 5.4.1, several simplifications have been made. For example, it was assumed that the process is strictly one-dimensional and that no oblique shock waves or reactive centers appear that accelerate the initiation of a detonation. Also, the formation of shock waves is often not as simple as shown in Figure 5.4.1.

5.4.2 Effects of Pipe Bends and Obstacles on Flame Acceleration.

5.4.2.1 Fluid and particle flow through pipe bends is a well-understood subject due to its associated practical problems in the process industry (Berger, Talbot, and Yao, 1983; Burgess, 1971; Green, 1999); however, little research has been carried out on explosions through pipe bends, a complicated problem involving the interaction between fluid dynamics, heat transfer, and (turbulent) combustion. In the first work carried out on this topic, Phylaktou, Foley, and Andrews (1993) showed that with a short tube a 90-degree bend can enhance both the flame speed and the overpressure for methane-air explosions

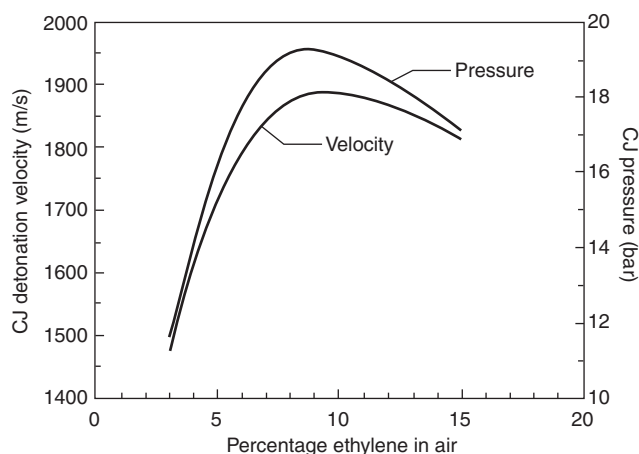


FIGURE 5.3.5 Chapman-Jouguet Detonation Velocities and Pressures for Ethylene-Air Mixtures.

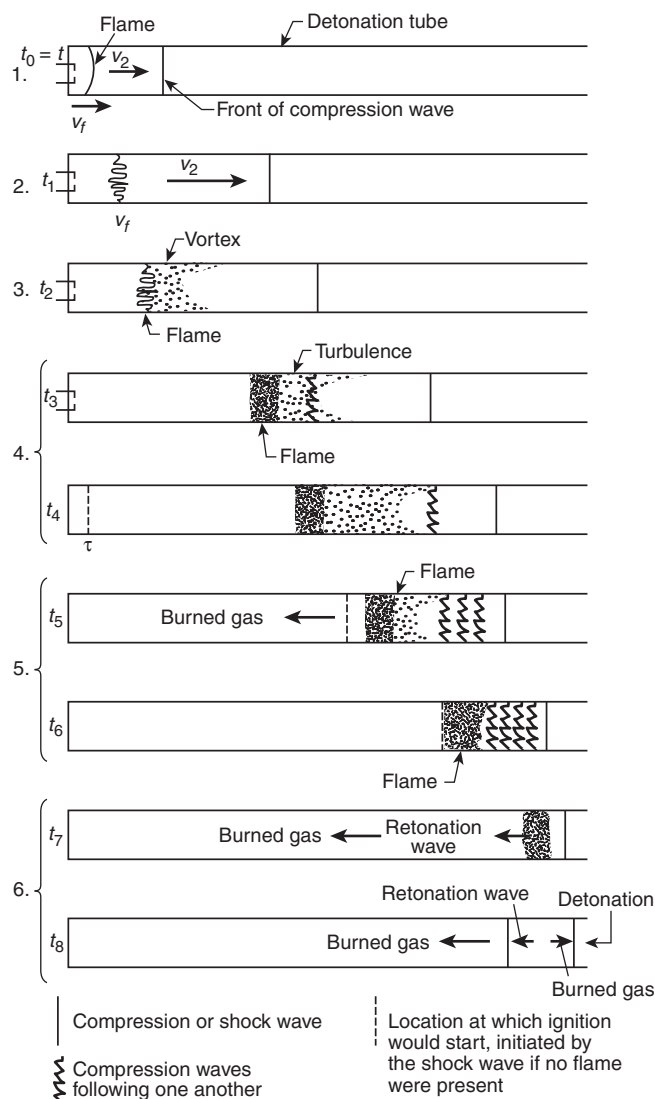


FIGURE 5.4.1 Depiction of Various Phases of the Development of a Detonation from a Flame.

compared with similar experiments carried out in straight pipes. The flame speed in these experiments was enhanced by a factor of approximately 5 and was equated to the effects of a baffle with a blockage ratio of 20 percent at the same position. Sato, Sakai, and Chiga (1996) investigated the effects of ignition position on the shape of the flame front and the flame speed for methane-air explosions using an open-ended small square channel containing a 90-degree bend. However, only a limited number of experiments were carried out, and no comparison was given to an experimental setup without the bend. A 24 percent enhancement of the flame speed after a 90-degree bend placed halfway down a tube was observed in propane-air experiments by Chatrathi (1992). The pipe diameter used for those experiments was 152.4 mm, and the pipe was open at the end farthest from the ignition source. Observations of the flame front traveling through a rectangular 90-degree bend were made by Zhou, Sobiesiak, and Quan (2006), who showed that after initially propagating as a flat flame the flame front took on the tulip configuration (Clanet and Searby, 1996;

Gonzalez, Borghi, and Saouab, 1992). As the flame reached the bend, the upper tongue of the tulip shape (the one propagating toward the outside of the bend) slowed down, relatively; however, the lower tongue (the one propagating toward the inside of the bend) began propagating more quickly around the inside of the bend, an effect the authors named “flame shedding.” Three-dimensional particle modeling of the flow around the bend showed that large vortices were created just downstream of the inside wall of the bend while flow followed a more streamlined pattern around the outside of the bend. This was in good agreement with latter constant temperature anemometry (CTA) observations made by Lohrer, Hahn, Arndt, and Grätz (2008), who showed that a bend induced a significant increase in turbulence over the first 30 percent of the inner diameter of the pipe immediately after the bend. At the same time, only a relatively small amount of turbulence was induced around the outer side. Unfortunately, in the study by Zhou et al., the bend was relatively close to the end of the tube, giving little opportunity to observe the effect of the bend on downstream flow patterns. Explosions (propane-air) have also been carried out in coiled pipes and pipes with multiple U-shaped bends (Frolov, 2008). While these configurations were able to produce fast DDTs, they are generally of more interest for pulse detonation engines (Roy, Frolov, Borisov, and Netzer, 2004), in which fast DDT is a requirement, rather than for industrial-scale pipework carrying potentially flammable gas (Blanchard et al., 2010).

5.4.2.2 Experiments in explosions in closed pipes containing baffles and 90-degree bends demonstrate the ability of a full-bore obstacle to accelerate the burning velocity of a number of gases and reduce the run-up distance required for DDT. It was shown that a 90-degree bend placed at a relatively short distance from the ignition point in a long tube had the ability to enhance flame speeds and overpressures and shorten the run-up distance to DDT. In terms of the qualitative effects on these parameters, they were comparable to a baffle-type obstacle with a blockage ratio (BR) of between 10 and 20 percent. It is expected that the flame speed enhancement caused by the 90-degree bend will be greater when the obstacle is placed farther downstream of the ignition point, due to the incoming flame having longer to accelerate and, hence, will create a greater amount of turbulence downstream of the bend. This work has contributed further to the argument that bends in a pipework system can have a significant effect on the combustion process, that they should be taken into account as part of a safety analysis, and that they should be considered in the placement of explosion protection devices such as flame arresters or venting devices. Although this work has shown some interesting effects, there are still many unanswered questions regarding the effects of obstacle position, multiple bends, and other full-bore obstacles. Interesting observations were also made on the variation of burning rates when the same pre-set variables are used, an effect that needs to be further studied to determine the exact nature of the interactions that can contribute to flame acceleration.

5.4.2.2.1 Methane air results are shown in Figure 5.4.2.2.1(a) and Figure 5.4.2.2.1(b).

5.4.2.2.2 Propane air results are shown in Figure 5.4.2.2.2.

5.4.2.2.3 Ethylene air results are shown in Figure 5.4.2.2.3.

5.4.2.2.4 Hydrogen air results are shown in Figure 5.4.2.2.4.

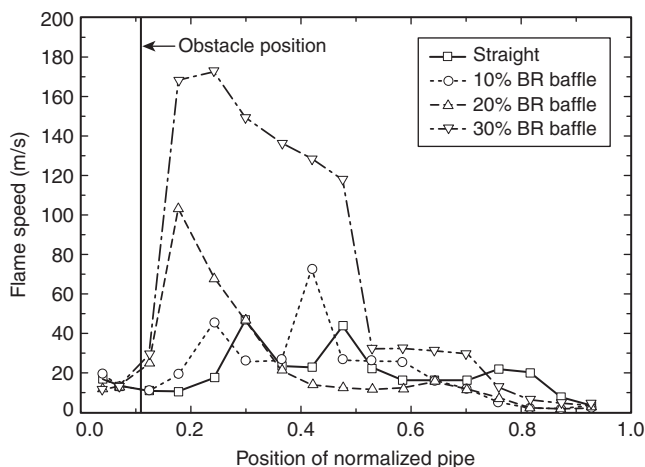


FIGURE 5.4.2.2.1(a) Flame Speeds for Methane-Air Explosions with a 10, 20, and 30 Percent BR Baffle.

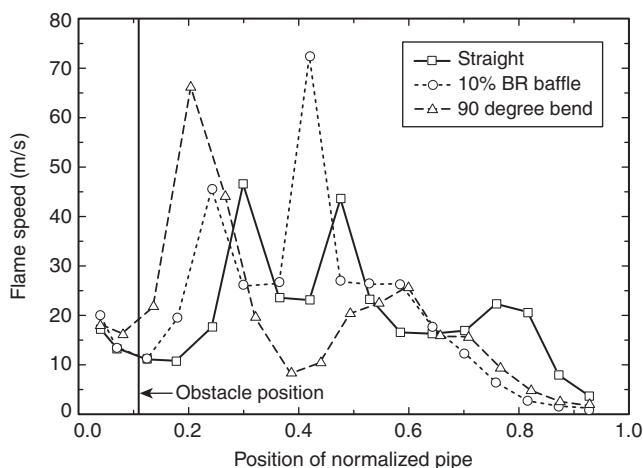


FIGURE 5.4.2.2.1(b) Flame Speeds for Methane-Air Explosions in Straight, 10 Percent BR Baffle, and 90-Degree Bend Configurations.

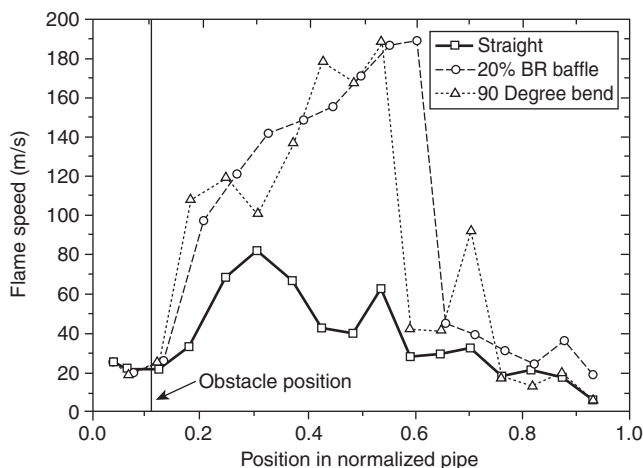


FIGURE 5.4.2.2.2 Flame Speeds for Propane-Air Explosions.