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Method of test for burning velocity measurement of A2L flammable gases

Méthode d'essai pour mesurer la vitesse d'inflammabilité des gaz inflammables A2L

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Foreword

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This document was prepared by Technical Committee ISO/TC 86, *Refrigeration and air-conditioning*, Subcommittee SC 8, *Refrigerants and refrigeration lubricants*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Safety classification and relative flammability properties of refrigerants are a critical part of ISO 817. The flammability limits of refrigerant gas in air, as described in Annex B of ISO 817:—[1)] give a partial measure of the relative flammability. Another dimension of flammability is how fast a substance burns, releases energy and spreads a flame. One can measure the rate at which a flame front moves through a cloud of refrigerant gas in air, or its burning velocity (BV). This document describes one method that can be useful for BV measurement, and thereby better quantify and compare relative flame fronts for some refrigerant classes. In this test, a flame is allowed to propagate upward (vertically) through a well-mixed, quiescent column of a refrigerant-air mixture enclosed in an open-ended glass tube. Optical systems are used to measure the upward velocity of the flame front.

The measurement of BV has been widely used in the past to compare highly energetic fluids, such as motor fuels and rocket propellants. The BV measurement of slow burning fluids, such as ammonia and fluorinated refrigerants can be more difficult to measure due to the inherent instability of a slow flame. The low rate of energy evolution from a slow flame makes it susceptible to quenching from a variety of sources. For slow burning refrigerants, turbulence and convection currents, can break the flame front, and hence quench the flame. In addition, the test chamber surface can quench free radical flame intermediates as well as extract some of the heat necessary for flame propagation. Gas-phase thermal radiation is also important for flames with low burning velocity. These effects are important to note as they tend to diminish and sometimes quench a weak flame.

The use of the vertical tube method for BV characterization of slow burning refrigerants was the subject of doctoral research which was used in Annex C of ISO 817:— and is the basis for this document.[1] In addition, ASHRAE research notes the use and limitations of the vertical tube technique.[2][3] While the basic framework of the method is relatively simple, some sophisticated imaging instrumentation and mathematics are necessary to extract an average local burning velocity separate from the bulk burning speed as the flame progresses up the tube. Since 2004 other laboratories have used the basic principle of vertical tube method and have shown acceptable results for reproducing the measurement of R-32, at 6,7 +/- 0,7 cm/s. Slower burning velocities (i.e. <4 cm/s) become more difficult to measure reproducibility, so variability may increase as flame instability is increasing. The lower burning velocity limit of this method, as described, is between 3 cm/s and 4 cm/s, depending on the actual design and geometry of the apparatus being used. The uncertainty of the measurement of flames that burn more slowly than R-32 has not yet been determined in any multi lab comparative testing. The appealing aspects of this test are the relative simplicity and low cost of its implementation.

1) Under preparation. Stage at the time of publication: ISO/DIS 817:2023.

Method of test for burning velocity measurement of A2L flammable gases

1 Scope

This document specifies a method of measuring the burning velocity (BV) of slowing burning refrigerants (< 10 cm/s) for use with other standards that utilize the BV for determining safety classification of refrigerants (e.g. ISO 817) or that use the BV in establishing requirements on the use of slow burning refrigerants (e.g. ISO 5149).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
blends
mixtures composed of two or more refrigerants

3.2
burning velocity
S_u
maximum velocity at which a laminar *flame* propagates in a normal direction relative to the unburned gas ahead of it

Note 1 to entry: This value is expressed in centimetres per second.

3.3
combustion
exothermic reaction between an oxidant (e.g. air) and a combustible fuel

3.4
compound
substance composed of two or more atoms chemically bonded in definite proportions

3.5
flame
space where combustion takes place, resulting in a temperature increase and light emission

3.6
flame propagation
combustion, causing a continuous *flame* which moves upward and outward from the point of ignition without the influence of the ignition source

3.7
flame propagation velocity
S_s
velocity at which the continuous *flame* moves upward and outward from the point of ignition without the point of ignition and without the influence of the ignition source

3.8
flame surface area
A_f
surface area of the *flame* generated during the combustion of the *flammable* gas

3.9
flammable
property of a mixture in which a *flame* is capable of self-propagating

3.10
quenching
effect of extinction of the flame near a surface due to heat conduction losses, absorption of active chemical species and viscous effects of the surface

3.11
refrigerant
fluid used for heat transfer in a refrigerating system, which absorbs heat at a low temperature and a low pressure of the fluid and rejects it at a higher temperature and a higher pressure of the fluid usually involving changes of the phase of the fluid

3.12
stoichiometric concentration
C_{st}
concentration of a fuel in a fuel-air mixture that contains exactly the necessary quantity of air (approximately 21 % O_2 / 79 % N_2 by volume) needed for the complete oxidation of all the compounds (3.1.4) present

4 General test method

4.1 General

The test method is based on:

a) the initiation of the combustion of the gas, or blends of gases, in a stagnant homogeneous mixture with air contained in a vertical cylindrical tube;

b) the observation and the recording of the flame propagation;

c) determining the surface area of the flame.

The burning velocity is a function of the flammable gas concentration in the total mixture with air. The burning velocity reaches a maximum in the vicinity of the stoichiometric concentration.

This test method involves the use of hazardous substances and therefore requires, for a safe handling and testing, the knowledge of safety parameters and prevention measures. These measures shall be the user's responsibility. However, general safety precautions are given in Clause 8.

4.2 Principle of the test method

The test method consists of initiating the combustion of a homogeneous mixture of a flammable gas (or a flammable mixture of gases) and air, contained in a vertical tube opened at the lower ignition end, and propagating a flame upwardly to the upper closed end; see Figure 1. In the early stages of this propagation, there is a phase of uniform movement during which the shape and the size of the flame are constant.

Taking into account the mass and species balance through the flame front, the burning velocity, S_u, is calculated from the knowledge of the flame propagation velocity, S_s, in the tube and the ratio of the flame front area to its base cross-sectional area. The volume of burned gas per second and per unit area, or the burning velocity, S_u, is obtained by dividing the mixture volume which is consumed per second, at the test temperature and pressure, by the flame surface area, A_f (the subscript "f" denotes the flame). The volume consumption of the mix per second is the volume swept by a cross-sectional area of the flame base, a_f, with a velocity equal to the flame propagation velocity S_s. Formula (1) is used to determine volume consumption per unit time.

$$S_u = S_s \times \frac{a_f}{A_f} \tag{1}$$

where

a_f is the cross-sectional area of the flame base;

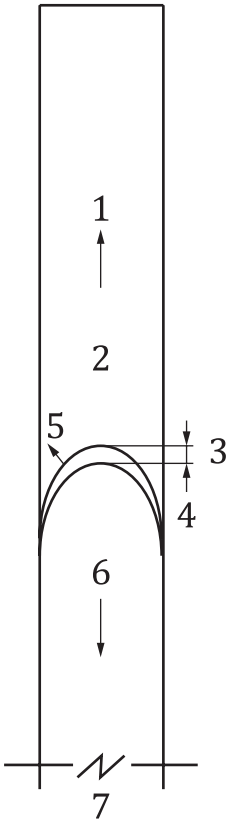
A_f is the flame surface area;

S_s is the flame propagation velocity;

S_u is the burning velocity.

NOTE The cross-sectional area of the flame base is equal to the tube cross-section reduced by the quenching area (the area between the edge of the flame and the tube wall).

At a given temperature and pressure, the burning velocity is only a function of the type of flammable substance and its concentration with the oxidant and is dependent to a limited extent on the experimental apparatus.



Key

1 direction of flame propagation
2 unburned mixture
3 flame front displacement
4 dx thickness of the combustion region
5 S_u
6 burnt gas
7 ignition

Figure 1 — Schematic of the flame propagation in a vertical tube

5 Measurement parameters

5.1 General

The measurement of the burning velocity requires the knowledge of the following three parameters of Formula (1):

a) the flame propagation velocity, S_s;

b) the flame front area A_f;

c) the cross-sectional area of the flame base a_f.

5.2 Flame propagation velocity

The flame propagation velocity in the tube is required for the measurement of the burning velocity. As a condition to the derivation Formula (1), only parts of uniform flame propagation shall be considered in the measurements (constant S_s).

The linear propagation velocity of the flame is obtained from the direct measurement of the flame front displacement determined by two successive images with a known time interval (30 Hz to 50 Hz) of the camera acquisition frequency. More than one succession of images shall be used to check that the flame propagation is uniform. An image treatment is necessary in order to enhance the flame front shape and to locate on both images an identical luminous spot (pixels with equal brightness level) that corresponds to the same location on the front and deduce the flame front displacement. This procedure is proved necessary with low luminosity flames since any uncertainty in the flame front displacement leads to an uncertainty in the flame propagation velocity and thus on the burning velocity.

5.3 Flame front area

The flame front shape cannot be generated by the revolution of a parabola nor by the approximation by an ellipsoid segment, even though in many cases this shape is symmetrical. An accurate method is needed to calculate the flame front area A_f. For an upward propagation, the flame usually shows a symmetrical front surface referred to the tube axis. For a uniform propagation, the shape of the flame front remains constant. Fast moving flames are almost hemispherical, the slower flames are somewhat elongated.

9.7 describes a mathematical and geometrical model to calculate the flame front area. In summary, the flame front profile is marked with fitting points (20 to 40 fitting points) then divided into two or more horizontal sections. The fitting points shall be selected on the rim of the most luminous zone on the flame front.

For each section a polynomial fit equation of appropriate order is made in order to give the best fit curve to the points selected on that section. The best fit gives the minimum deviation of the fit curve to the fitting experimental points. The area of each section shall then be calculated separately by dividing it into many small elementary sections. The area of each elementary section is then calculated from the assumption of a revolution shape., taking into account the bottom edge of the flame not being horizontal.

5.4 Cross-sectional area of the flame base

The cross-sectional area, a_f, of the flame base shall be calculated from knowledge of the diameter d measured at the base of the flame as illustrated in 9.7. In that case, use Formula (2):

$$a_f = \frac{\pi d^2}{4} \tag{2}$$

where

a_f is the cross-sectional area of the flame base;

d is the diameter of the flame base.

6 Test method

6.1 General

Measuring the burning velocity in a tube consists of

a) propagating a flame in a vertical transparent tube, opened at the lower ignition end, closed at the other upper end, and filled with the flammable mixture,

b) measuring the velocity of the flame propagating along the tube, and

c) recording the flame front area with a camera.

Measurements are performed at atmospheric pressure.

The test bench layout is shown in Figure 2. The main elements of the bench are

— mixing vessel,

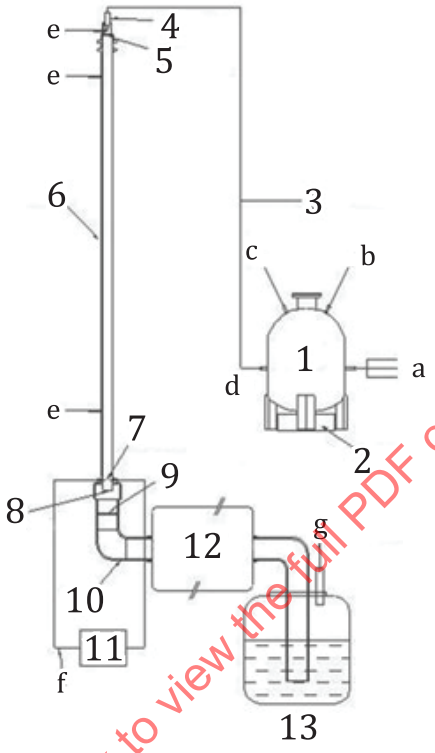
— ignition system,

— camera,

— test temperature control, and

— gas treatment systems.

NOTE To minimize pressure feedback effects, typically the scrubber system is not attached during the ignition and burn portion of the testing (see Figure 8).



Key

1	mixing vessel	a	From gas supply tanks.
2	magnetic stirrer	b	Pressure measurement.
3	purging gas line	c	To vacuum pump.
4	tube inlet	d	To inlet tube.
5	quenching and smoothing screen	e	Temperature measurement.
6	test tube	f	Supply power to ignition.
7	electrodes	g	Extraction to hood.
8	fitting orifices		
9	quenching screen		
10	poly(vinyl chloride) pipe		
11	igniter		
12	gas expansion tank		
13	collection tank with neutralizing solution		

Figure 2 — Schematic of the test bench

6.2 Gas handling and mixtures preparation

The gas mixture preparation is described in ISO 817:—, 6.1.3. If used, the scrubbing system described in 6.6 should be disconnected so that the expansion volume is not filled with a flammable concentration.

The constant composition blend is then caused to flow through the tube until the gas mixture displaces at least thirteen times the air volume of the tube. Care should be taken to ensure that the gas mixture exiting the bottom of the tube is properly vented. Once the desired mixture has been achieved in the tube, the mixing vessel shall be isolated from the tube before ignition to prevent ignition of the gas in the vessel. It is good laboratory practice to measure the concentration of the gas mixture in the tube to ensure the methods employed adequately accomplish this objective. A paramagnetic oxygen analyser is effective for this determination.

It is recommended that all the components, connections and parts of the test bench be resistant to their use with corrosive gases, such as ammonia and copper, or other oxidation reactions. Stainless steel can be used, or any other material identified to be adequate for use with the substances to test.

6.3 The test tube

6.3.1 General

The test tube shall be designed to ease the flame propagation with less possible disturbances, especially at the ignition level and the first stage of flame propagation; see Figure 3. The design of the test tube should look into the following points:

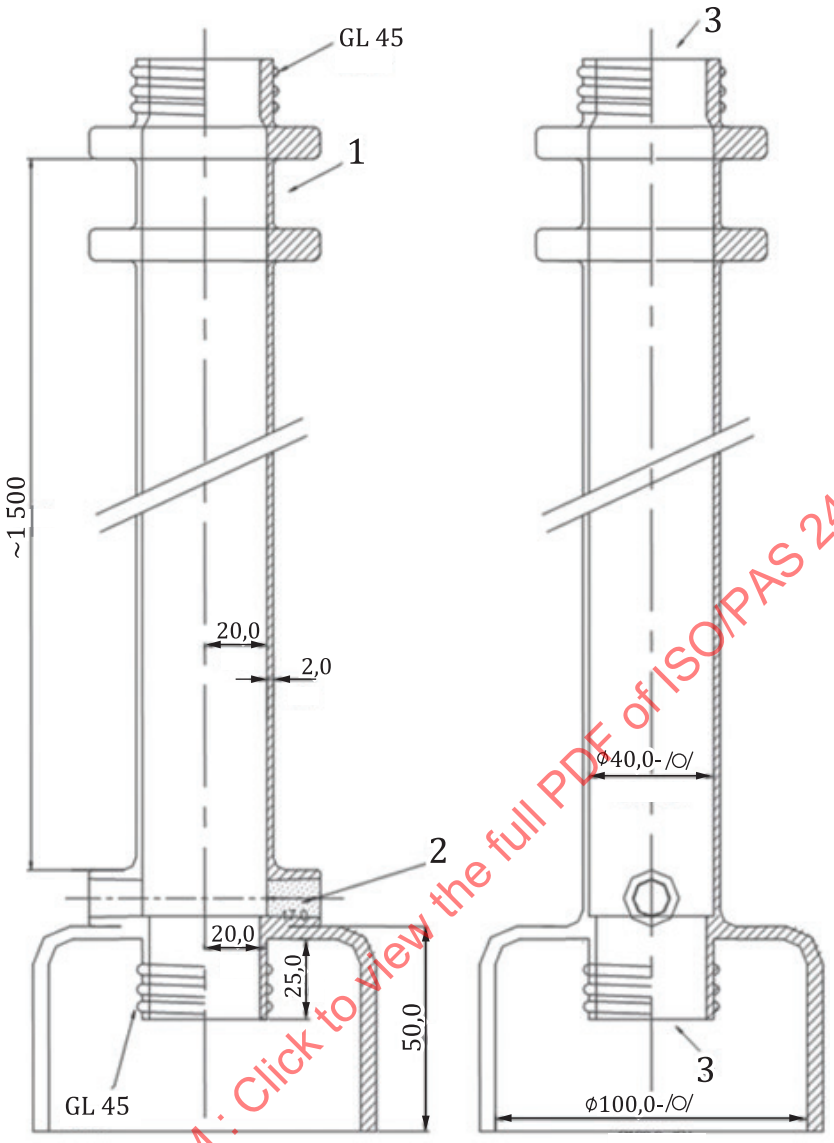
a) the ignition system, the quenching screen, and the damping orifice should be designed as close as possible to the outlet of the tube;

b) the outlet of the tube (at the lower end) should be designed to facilitate its connection to the extraction and gas treatment systems;

c) the tube should be fixed on a vertical support and at a level below the ignition system to prevent the fixing support from disturbing the flame propagation (excessive cooling) or any obstruction of the flame photography;

d) technical limitation with glass design and work should be considered as well.

Dimensions in millimetres



Key

1 fixing housing
2 RIN 10/19 housing for electrodes
3 inlet tube end

Figure 3 — Test tube design and main dimensions

6.3.2 Dimensions

The tube shall be made of glass, 1,2 m long with a 40 mm internal diameter. The diameter has been chosen as a compromise between narrower tubes that increase the quenching effect but allow more stable propagation regimes, and larger tubes in which the losses to the walls are smaller but associated with an increase of instabilities.[1][4] The choice of the 40 mm diameter has been shown[5] to be the most convenient for measurement of burning velocities below 40 cm/s. It withstands a pressure of 100 kPa above the atmospheric pressure even if the overpressure is very limited, the bottom end of the tube being the open end.

NOTE Unstable regimes are frequent with fast propagating flames; see 9.3. The tube length is based on dimensions from previous research. Any great change in that length affects the flame propagation regimes and its stability only when working with high burning velocity compounds.

6.3.3 Position

The tube should be placed in a vertical position to reduce possible deformations of the flame front from buoyant effect and to ensure a more symmetrical shape. In this position the flame propagates upwardly, the ignition occurring at the lower end of the tube.

6.3.4 Tube ends

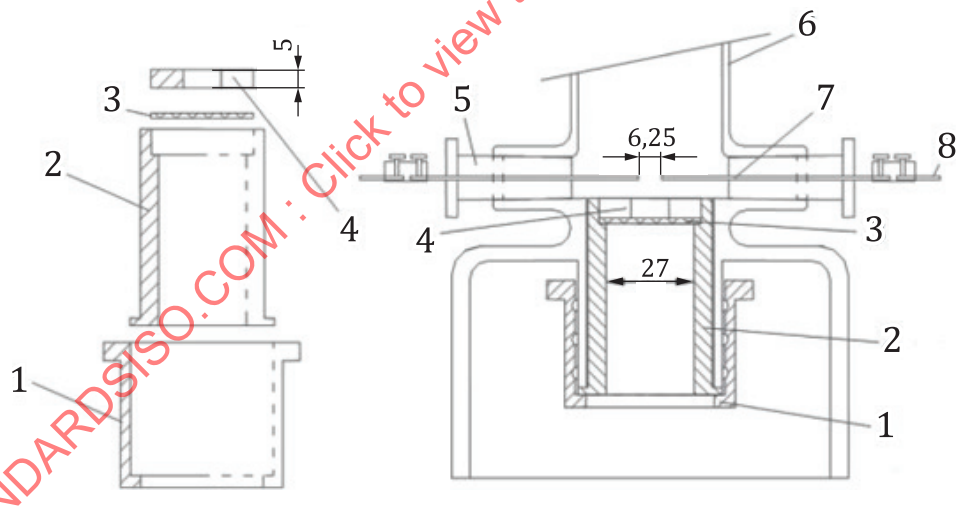
The bottom end of the tube shall be open to the atmosphere. At this end are located the ignition system and the damping orifices. A GL45 cap can be used to maintain the system in place (see Figure 4 and Figure 5). With harmful components present in the combustion products (toxic or corrosive, e.g. HF, HCl, NH_3), the lower end should be connected to a gas post-treatment system (see 6.6). This design does not allow excessive pressure build-up and the combustion products can freely exit the tube or expand in a 125 l tank if the gas treatment system is used.

The upper end of the tube should be connected to the mixing vessel. The mixture flows out from mixing vessel into the tube and out of its bottom end. A GL45 cap shall be used to fix the inlet system. This end shall be closed before the ignition and until the end of flame propagation.

6.3.5 Interchangeable damping orifices

The flame propagation velocity and the flame shape vary with the type of flammable substance and the composition of its mixture with the oxidant. Adjusting the exit diameter at the lower open end by insertion of calibrated orifices helps stabilize the flame front shape by reducing the instabilities and damping the acoustic effects[6][7][8][9] and therefore helps to reproduce a better shape of the flame front. The diameters of the damping orifices for a tube of 40 mm internal diameter vary from 9 mm to 11 mm (see Reference [9] for detailed calculation). The damping orifices are recommended with relatively high burning velocities (i.e. higher than 25 cm/s).

Dimensions in millimetres



Key

1	cap for GL 45 tip	5	RIN 10/19 polytetrafluoroethylene (PTFE) stopper
2	polytetrafluoroethylene (PTFE) body	6	test tube
3	quenching screen	7	1 mm diameter electrode
4	polytetrafluoroethylene (PTFE) fitting orifice	8	power supply connection

Figure 4 — Drawing of the lower end of the tube showing the ignition electrodes and the damping (fitting) orifice

6.3.6 Flame quenching

Quenching screens shall be mounted at both ends of the tube, resistant to the reaction with HF and NH_3, to prevent any hazard to the surroundings. The quenching screens shall have a mesh size of 1 (+ 0,5 - 0,1) mm.

6.3.7 Tube glass type

The spectral emissions of most flames are presumed to be in the range of 250 nm to 600 nm. To prevent excessive losses, it is important to compare the glass transmission profiles before selecting the type of glass (e.g. silica glass, borosilicate glass).

6.3.8 Tube purging with test mixture

The test tube shall be purged by the mixture under test with a continuous flow from the mixing vessel with an equivalent volume flow rate which represents at least 13 times the internal tube volume. The gas mixture shall enter the upper end of the tube and exit from its lower end. The lower end can be closed after purging to avoid any possible concentration variation by dilution in the neighbourhood of the electrodes. This end is opened to the atmosphere just before ignition.

6.3.9 Tube etching

The presence of substances such as hydrogen fluoride (HF) or hydrogen chloride (HCl) with water residues in the combustion products of HFCs or HCFCs results in tube etching so that after several tests (30 to 50 depending on the cleaning process) the tube turns opaque with an almost white colour (see Figure 5).

For this reason, the tube shall be purged immediately after the end of the flame propagation with a stream of dry nitrogen. Afterwards, a wet wiper may be introduced inside the tube to clear all deposits on the inner wall. A stream of nitrogen may be again circulated inside the tube to remove water deposits from the wiper.

With this cleaning technique it is possible to use the same tube for a larger number of tests before the etching effect becomes noticeable and the tube needs to be discarded.

Figure 5 — Tube etching due to hydrogen fluoride

6.4 Ignition

6.4.1 General

The ignition source can affect not only the flammability limit results but also the flame propagation regime. Analyses of spark ignition have been made by many researchers (Reference [10] gives a survey) and deal with the electrode arrangement, type (flange electrodes for instance), material and size, the electrode gap, the spark duration and the breakdown voltage as well as the effect of these on the minimum ignition energy.

The ignition system described in this test method has the same characteristics as the ignition system used in the ASTM E681 flammability test method in terms of the electrode dimensions, the gap distance, the ignition time and the power supply. This similarity helps to ensure that the vertical tube burning velocity method and complements the ASTM flammability method.

NOTE These ignition specifications are also very similar to those specified in DIN 51649-1 (which is meant by the flammability limits).[9]

6.4.2 Ignition type

The mixture is ignited with an electrical spark produced by two electrodes.

6.4.3 Positioning

The ignition occurs at the bottom end of the tube. The electrodes are fixed diametrically opposite on the tube, centred on its axis and positioned 5 mm to 10 mm above the upper surface of the interchangeable orifices. The electrodes shall be fixed using RIN 10/19 PTFE stoppers lodged in specially conceived RIN 10/19 housing (see Figure 4)

6.4.4 Electrodes

The electrodes are made of tungsten with 1 mm diameter. The gap between the electrodes is 6,4 mm. When necessary, a special calibrating cylinder can be inserted inside the tube and in-between the electrodes in order to verify their eccentricity and to ensure a correct gap distance.

To ensure good ignition conditions, especially near the lower and upper propagation limits, the electrodes shall be repeatedly cleaned of any deposit.

6.4.5 Power supply

Power to the ignition electrodes shall be supplied by a transformer with an output of 15 kV, 30 mA. Usually, such high voltage is not required except with compounds having a high breakdown potential. The power supply system is connected to the electrodes using insulation rated for at least 15 kV to avoid short circuits and poor contacts avoiding overheating.

6.4.6 Ignition time

The ignition time shall be set at (0,3 ±0,05) s by adjusting the spark duration with a timer. This time duration has been proved to be the most appropriate for flammability limits measurements.[9]

Ignition should not be made immediately after filling the tube with the corresponding mixture, but 5 s to 10 s later, permitting the turbulence to cease in the tube.

NOTE The excessive energy release from this ignition system might be responsible for emitting waves inducing turbulence in the flame front and the mixture ahead of it. Flame propagation is not steady close to the ignition source.

6.5 Flame front visualization

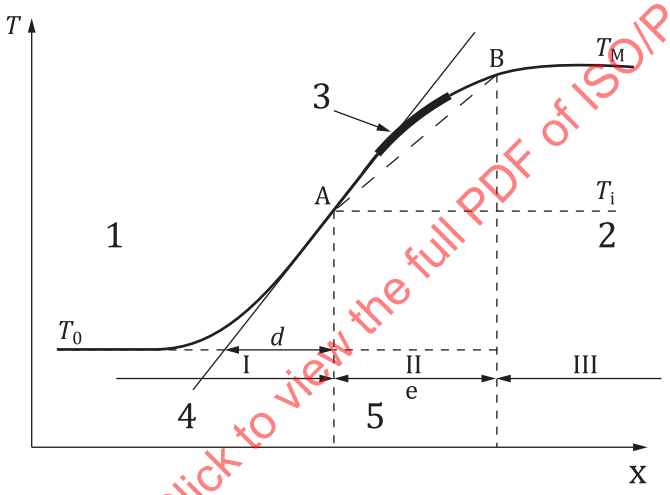
6.5.1 General

Direct photography is used to record the flame front images. These images are used for the calculation of the flame propagation velocity as well as its surface area.

6.5.2 Luminous zone and direct photography

The burning velocity measurement Formula (1) is based on the calculation of the flame front area at the preheat zone layer. With direct photography, the luminous zones of the flame are revealed. Therefore, any measurement made with this photography technique shall be based on the zone of the flame of most intense illumination. This zone corresponds to the region of the flame between the point whose temperature is equal to the ignition temperature and the point at the end of reaction (see Figure 6). The relative uncertainty in the burning velocity assessed with the flame front area calculation based on flame profiles from direct photography is 6,5 %.

NOTE The 6,5 % relative uncertainty can be reduced and the correct surface position can be better approached if the profile of the outer edge of the luminous zone is shifted outwards by a distance equivalent to the luminous zone width.



Key

1 unburned gas
2 burned gas
3 luminous zone
4 pre-heat zone
5 reaction zone

Figure 6 — Temperature profile along a combustion flame and luminous zone

6.5.3 Flame emission spectra

The spectra peaks from combustion depend on the type of substance combusted and the radicals formed such as OH, HCO, CH, C_2 and C_3. From a qualitative point of view, it can be stated that the typical peaks for maximum emission, and even sometimes a higher-level continuum, are in the range of 250 nm to 600 nm for HC and HFC flames.

6.5.4 Acquisition camera

A digital camera shall be used to visualize the flame propagation. The flame front images shall be recorded and saved for further treatment (flame propagation velocity measurement and flame front area calculation).

When identifying the camera to run the tests, the characteristics of exposure time and acquisition rate shall be selected as a function of the velocity range being measured. With very fast flames, a high acquisition rate and small exposure time are needed (i.e. <1 ms). The spectral response of the camera shall be also taken into account and the higher efficiency of the quantum efficiency curve shall cover the range of typical wavelength of the flames being visualized.

NOTE A set of adjustments and different operating modes, such as the resolution, image enhancements, image rate, exposure time, number of frames during record, pre-/post-trigger and parameters for image output, performed via an appropriate interface, can help in adapting the images to the type of flame front being recorded. A set of lenses can also be used to zoom and focus the optimized photography frame.

6.5.5 Exposure Time

Setting the exposure time is necessary before starting the photography of the flame propagation to best reproduce the flame front shape and increase the precision of its area measurement.

Since there is no defined relationship between the flame propagation velocity and its more or less luminous aspect, for fast and low luminous flames the tester has to find a compromise for setting the exposure time. A higher exposure time compensates the low luminosity but results in an imprecise shape of the flame front due to its displacement during the exposure time.

For measurements around the stoichiometry, the recommended exposure times are of 1 ms or less. This value is determined by practical experience and depends on the camera.

6.5.6 Positioning

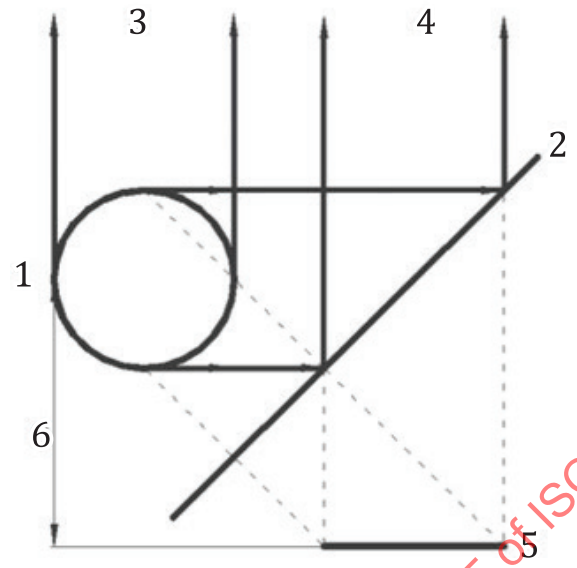
The camera recording field shall be adjusted to the appropriate position and height of the tube where the flame movement is known to be uniform. Only images taken at the same level of the lens axis shall be used to calculate the flame front area and reduce the imprecision on the flame front dimensions.

6.5.7 Scaling and optical distortion

Scaling of the flame images to the real flame front dimensions can be achieved by taking a photo of a graduated ruler placed along the tube in order that the graduations coincide with a layer crossing the centre of the tube and at right angles to the camera axis.

NOTE The optical deformation due to the tube wall geometry is negligible.

A mirror at 45° is placed beside the tube in order to identify the irregularities of the flame front surface and to increase the accuracy of the tests by ensuring the correct assumptions for the flame front area calculation. With the camera facing both the tube and the mirror, recorded images give both the front view and the side view of the flame front (see Figure 7). Note that the plane in which the mirror image is placed is located behind that of the direct photography. If used for calculation, these images shall be scaled to the same vertical layer crossing the centre of the tube and at right angles to the camera axis.



Key

1 tube
2 mirror
3 face view image beam
4 side view image beam
5 actual side view image position
6 displacement

Figure 7 — Schematic of the face and side view image as received by the camera

6.5.8 Resolution of the flame images

The essential uncertainty in the measurement of the burning velocity with the tube method is related to the image resolution for the flame propagation velocity, the scaling factor, and the flame front area. An increase in the resolution provides more accurate results, but to the extent where the points fitting on the flame front image becomes independent of the pixels of small dimensions.

6.6 Purge, exhaust and gas treatment systems

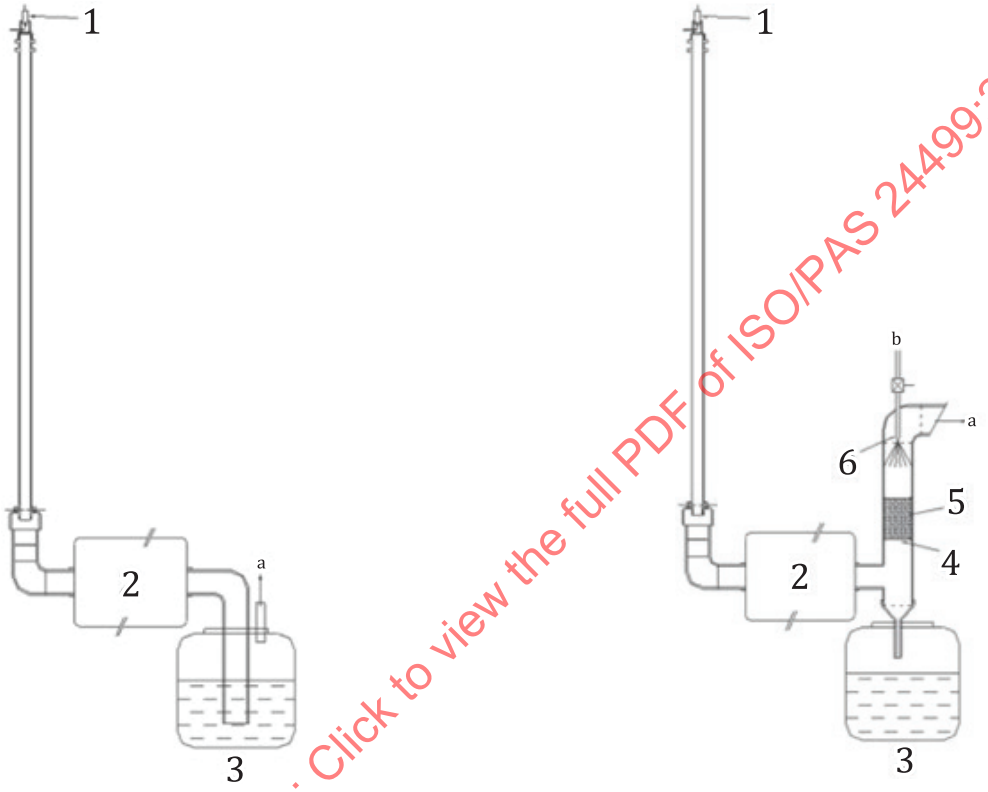
The test apparatus shall be cleaned thoroughly after each test to remove the remaining combustion products and effluents from the previous test and to make sure that the combustion products shall not harm the personnel or damage the environment. An appropriate treatment process of the combustion products, especially with fluorinated gases, shall be put in place: the extraction of the combustion products shall be performed rapidly at the end of the test in order to neutralize the HF or HCl, which in some cases constitutes more than 30 % of the combustion products, and reduce the corrosion of the test tube (a small amount of moisture makes it very corrosive). For this purpose, an ad hoc treatment system and exhaust gas clean-up is designed and installed at the outlet of the test apparatus, permitting the removal of the corrosive substances by splashing the exhaust gas into a basic water solution (e.g. NaOH). The treatment system also includes an expansion tank connected between the gas treatment system and the lower end of the tube to simulate a constant pressure expansion condition (see Figure 8).

An extraction fan evacuates the combustion products from the tube, through the expansion tank and basic water solution and then the clean gas to the hood.

If needed, a water scrubbing system can be used instead of a splashing system. In that case a cone nozzle can be used for example to spray water onto the upward exhaust gas flow. The acid water is collected at the bottom and drained into a larger tank filled with a basic water solution to neutralize the acid water.

The water solution tank should be emptied regularly, and the acidity of the water solution checked to guarantee safe handling.

NOTE If necessary, two treatment systems can be placed in series to achieve a more complete removal.



a) With splashing **b) With scrubbing**

Key

1 tube inlet
2 gas expansion tank
3 collection tank with neutralizing solution
4 support screen
5 scrubber
6 nozzle
a Extraction to hood.
b Water supply.

Figure 8 — Gas treatment system

6.7 Test temperature setting

The test should be conducted at 23 °C. A test temperature of 23 °C may simply be achieved by controlling the temperature in the test room. Since the flame propagation is temperature sensitive, the temperature

gradient along the tube should minimized (e.g. to less than 1 K). This may be achieved by an appropriate circulation and control of a temperature-controlled air stream.

6.8 Experimental protocol for mixtures prepared using partial pressure technique

The following protocol is applied for running the tests when the partial pressure technique is used to prepare the mixtures.

a) The following items shall be checked before starting a new test:

   1) recording the reference scale of the camera to that of the real flame dimension (pixels/m, or equivalent);

   2) clean the tube by dry gas purging (air or nitrogen);

   3) check the electrodes gap distance and eccentricity;

   4) select the appropriate exit orifice diameter.

b) The mixing vessel and all connecting pipes and tubes shall be first evacuated to a pressure of 10 Pa abs or less.

c) The mixing vessel shall be then filled with the different mixture components, each at its corresponding partial pressure. The connections shall be evacuated each time a new gas is introduced into the mixing vessel. The magnetic stirrer should be turned on at the start of the process and for at least 5 min after the end of the filling process.

d) The mixture can be then allowed to leave the mixing vessel, circulate through the tube, out from its lower exit end and to the extraction hood. An equivalent volume of at least 13 times the internal volume of the tube is circulated.

e) The upper end of the vertical tube shall be closed first and then the lower end immediately after it to prevent any possible dilution or concentration changing within the electrodes region.

f) 5 s to 10 s should be given for the mixture inside the vertical tube to become quiescent.

g) The lower end shall be opened gently to avoid any perturbation or concentration changes around the ignition region, and then ignition is made. Just before ignition, the camera should be activated and the images are recorded.

h) After the end of the flame propagation, quenched at the upper end of the tube, the combustion products are driven out by a stream of nitrogen or air circulated inside the tube. In the case of harmful combustion products, the gas treatment system shall be installed and used.

7 Evaluation and expression of results

7.1 General

Test burning velocity is validated by Formula (3):

$$S_u = S_{u,max} a(\phi - \phi_{max})^2 \quad (3)$$

where

S_u is the burning velocity;

$S_{u,max}$ is the maximum burning velocity from the second-order polynomial fit to the experimental points;

Φ is the equivalence ratio at the burning velocity;

Φ_{max} is the equivalence ratio at the maximum burning velocity;

a is a fit constant

In a few cases, Formula (3) does not achieve the best fit to the burning velocity experimental results. Other adequate fitting equations should then be elaborated. The experimental points can also be split into two parts and for each, a separate fitting equation can be used.

NOTE In general, the maximum burning velocity is met at an equivalence ratio between 1,00 and 1,15.

7.2 Uncertainty

7.2.1 Uncertainty in the burning velocity

The total relative uncertainty of the burning velocity measurements as described in this International Standard is estimated between 7 % and 10 % and is due.

a) primarily to uncertainties in the flame front area calculation (65 % of the total uncertainty), and

b) the flame propagation speed measurement (35 % of the total uncertainty).

NOTE As described by Takizawa et al.,[2][3] the method is not usable for burning velocities below 4 cm/s because the rising, hot, burned gas bubble controls the flame propagation rate, not the burning velocity of the mixture.

7.2.2 Uncertainty estimation of concentrations

The concentrations of the mixtures as prepared with the partial pressure method are subjected to an uncertainty arising mainly from:

a) pressure transducer measurement;

b) ideal gas law used to derive the densities from the pressure and temperature. With air being the major component in the mixtures, the mixture state at pressures between 300 kPa and 400 kPa abs is not very far from the ideal state. In that case the relative uncertainty in the density is evaluated to 2 % whereas it can be neglected for pressures below 100 kPa abs,

NOTE The greater part of the uncertainty in the concentration arises from the ideal gas law assumption. For concentrations as high as 30 % volume fraction, the absolute uncertainty can be estimated at 0,6 % volume fraction or 2 % relative. For concentrations as low as 2 % volume fraction, the absolute uncertainty can be estimated at 0,08 % volume fraction and the relative uncertainty at 4 %.

The uncertainties in the burning velocity measurements and the mixture concentrations shall be determined specifically for each test bench.

8 Safety precautions

8.1 The safety recommendations are made for a proportion of oxygen in the air no higher than 21 % volume fraction.

8.2 For high burning velocities (>30 cm/s), it is recommended to make the tests starting from the lowest LFL of the components and gradually increasing the concentration. This is necessary to avoid explosions

with fast propagating flames near the stoichiometric concentration. An excessive restriction of the tube exit end with the interchangeable orifices shall be avoided.

8.3 Appropriate personal protective equipment (PPE) shall be employed by the test bench user (e.g. gloves, eye and head protection, etc.). Best practices suggest having personnel training in potential system hazards and HF safety kits available. HF compatible PPE should be used following safety program protocols.

8.4 The ad hoc gas treatment system shall be manipulated with caution because of its content of corrosive substances. The treatment system shall be sealed, and an extraction fan should be used to avoid any inhalation of the combustion products.

8.5 The high voltage ignition system, connections and electrodes should be handled with care and protected to prevent any direct contact. For safety reasons, potential ignition sources other than that intended for the testing should be avoided (e.g. switches, electrical contacts).

8.6 Quenching screens shall be mounted on both ends of the test tube. An additional quenching screen shall be placed at the entrance to the expansion volume to prevent any ignition hazard within that volume.

9 Overview on flame shape, propagation regimes and stability

9.1 Flame shape

When considering a combustion wave propagating from the open to the closed end of the tube, the unburned gas ahead of the wave is contained by the tube wall so that it forms a stationary column. The thermal expansion within the wave generates a continuous flow of burned gas towards the open end. The main parameters contributing to the establishment of the flame front shape are the following:

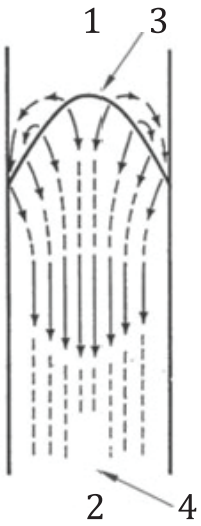
a) viscous drag responsible for flow retarding at the wall and acceleration in the centre of the tube (higher pressure thrust in the centre than near the wall);

b) unburned gas flow away from the flame front at the centre and towards it at the edges (the unburned gas ahead of the flame is pushed towards a closed end);

c) convection effect of burned gas resulting in an elongated front with slower propagating flames whereas the front takes an almost spherical shape with fast propagating flames;

d) constant burning rate in a direction normal to the flame front.

The balance between all of the above-mentioned effects seems to be requirements for maintaining the stability of the flame front during uniform movement (see Figure 9).



Key

1 closed end
2 open end
3 unburned gas
4 burned gas

Figure 9 — Direction of flow and particle velocity for laminar combustion wave propagation from open to closed end of the tube

9.2 Flame propagation regimes

With high burning velocities, the propagation usually develops in three distinct stages or regimes with two possible types of movements. The three stages can be distinguished either by flame structure or the amplitude of pressure and flame oscillations as well. The flame movement consists of one of the two following movements:

a) uniform movement;

b) vibratory movement.

The regime of flame propagation can develop into the following respective stages.

— After ignition, the flame propagates smoothly across the first part (first stage) of the tube at a uniform velocity which depends on the mixture and the tube length.

— An oscillatory motion of the flame can superimpose after the first stage. These oscillations begin with the appearance of a cellular structure in the flame front. The onset of oscillation and vibrations during propagation is the result of a coupling between flame and pressure oscillations in the gas.

— As the flame progresses, the tube becomes increasingly filled by hot combustion products and hence the basic frequency of the oscillation rises. The flame front can be subject to violent reciprocating motions and would accelerate steadily until the appearance of the turbulent propagation regime, leading to a large instability level, which persists until combustion is complete.

The termination of the uniform movement by a vibratory motion of flame always occurs when ignition is done at the opened end of the tube, the only exception being with slow burning mixtures, in which combustion may proceed at a uniform rate over a major part of the tube length.

NOTE 1 Measurements in a 40 mm tube of burning velocities below 23 cm/s[9] showed almost no flame acceleration. Compounds having burning velocities below 10 cm/s have been witnessed to propagate with velocities not exceeding 25 cm/s.