Influence of Tube Dimensions on Flame Behavior near Lean Flammability Limits

Jozef Jarosinski and Artur Gutkowski
Department of Heat Technology and Refrigeration, Technical University of Lodz
Lodz, Poland.
jarosin@ck-sg.p.lodz.pl

Introduction

Understanding the mechanism of flammability limits is of great practical and theoretical significance. In most cases these limits are determined in a vertical tube [1]. Usually the limits are different for upward and downward propagating flames [2]. It is evident that gravity influences the observed flammability limits. Empirically determined values of such limits depend on the Lewis number, kind of fuel and mixture concentration. For methane flames the lean-limit is $\phi = 0.53$ for upward propagation and $\phi = 0.59$ for downward propagation [2]. For propane flames both limits are practically the same $\phi = 0.53$ [3]. The role of the distance between channel walls, on the flammability limits, is not clear for tubes with cross-section greater than that of the standard tube. Opinions on the influence of a distance between vessel walls on the flammability limit (and quenching limit) of downward propagating flames have been presented in earlier studies, among other in [4, 5]. However, careful analysis of those sources shows insufficient experimental foundation of the existing opinions concerning relationship between the flammability limit and channel dimensions. Some of those opinions followed nothing but theoretical predictions.

The purpose of the present study is to find reliable experimental evidence of the influence of the channel dimensions on the flammability limit. A transition from an upward propagating spherical flame to a downward propagating flat one, in a vertical tube, is investigated in every detail. The flame behavior near the limits depends on mentioned earlier parameters such as the Lewis number, kind of fuel, mixture concentration and additionally on size of the tube. The detailed mechanism of flame quenching during its downward propagation in lean limit mixture is also studied. The ability of such flame to propagate freely downward is analyzed.

The emphasis of this study is on detailed observation of flame behavior under flammability limit conditions. The implications of flame behavior on the mechanism responsible for the extinguishment of downward propagating lean-limit flames are discussed in every respect.

Experimental Details

To study the influence of the vessel dimension on the flammability limits four different tubes were used in experiments with the following cross-sections: 50mm×10mm, 50mm×50mm, 125mm×125mm and 250mm×250mm. The 50mm×50mm, square flammability tube, about 1.8m long was equivalent to standard flammability tube, and the results obtained in this tube would serve as reference parameters. The length of the other tubes was 0.5 m and 0.8m. Two opposite walls of all of these tubes were built from schlieren quality glass plates.

The tubes were filled with the mixture by displacement. Lean methane/air and propane/air mixtures were used in the study. About 10 tube volumes flow through the tube before each experiment. During the experiments the top end of the tube was always open. In part of the experiments a schlieren method was used to record flame propagation. The schlieren system used one parabolic mirror of 0.3m diameter and 2.5m focal length and a horizontal knife-edge. The photographic records of flame propagation were made with a conventional Panasonic S-VHS video camera. In some experiments a mirror was placed at the bottom closed end of the tube to observe flame propagation from the bottom.

Results

Flame initiated by a spark ignition is risen upward by buoyancy forces in a form of increasing its diameter spherical flame kernel (see Figs 1 and 2). Buoyancy velocity of limit flame (5.25% CH_4) increases with an increasing diameter of a flame kernel (Fig. 2). The evolution of an initially spherical flame kernel into a shape shown in Fig. 1 is caused by a velocity field created by gravity [6]. Deformation of the bottom part of the flame kernel is observed in very lean mixtures and in large tubes. Transition to rich mixture decreases the inner cone of the flame kernel. Small size of the tube produces similar effect.

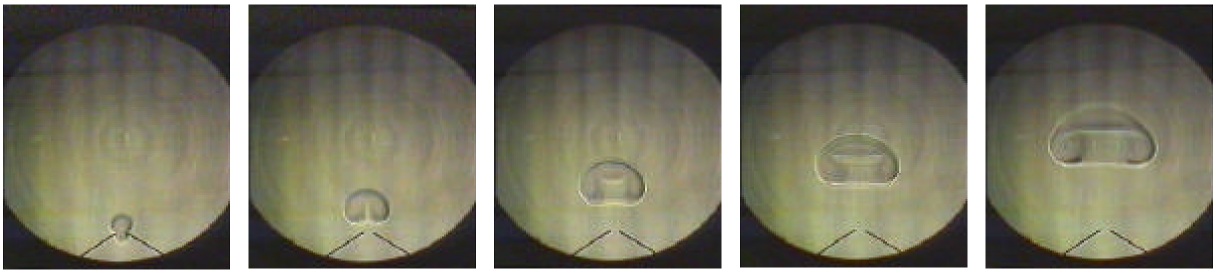

Fig .1. Flame development in a mixture 5.25% CH_4. Square tube 250mm $\times$ 250mm $\times$ 800mm. Time interval between frames 0.08 sec.

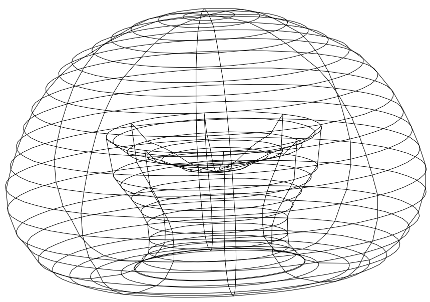

Fig. 2. Image of a flame shape at the base of the fourth frame from Fig. 1.

It is worth to mention that the velocity of a downward propagating limit flame is approximately the same for methane/air and propane/air mixtures and is close to laminar burning velocity of these mixtures. Methane flames can propagate upward in leaner methane/air mixtures, with smaller laminar burning velocities, in comparison with downward propagation, under the influence of preferential diffusion ($Le = a/D < 1$). Therefore, lean methane flames meet very deep deformation on the bottom part of the flame kernel. The inner part of the flame kernel is created by a luminous flame front, but with very small burning velocity, which is lower than appropriate components of a velocity field. On its way upward under buoyancy forces the flame touches the side walls of the tube and since that moment its lower part behaves very unstable (Fig. 4).

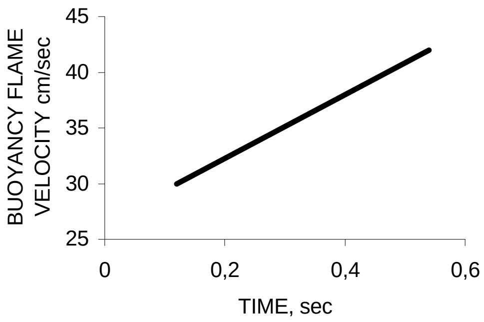

Fig. 3. Buoyancy velocity of a flame kernel calculated at the base of video film represented in Fig.1.

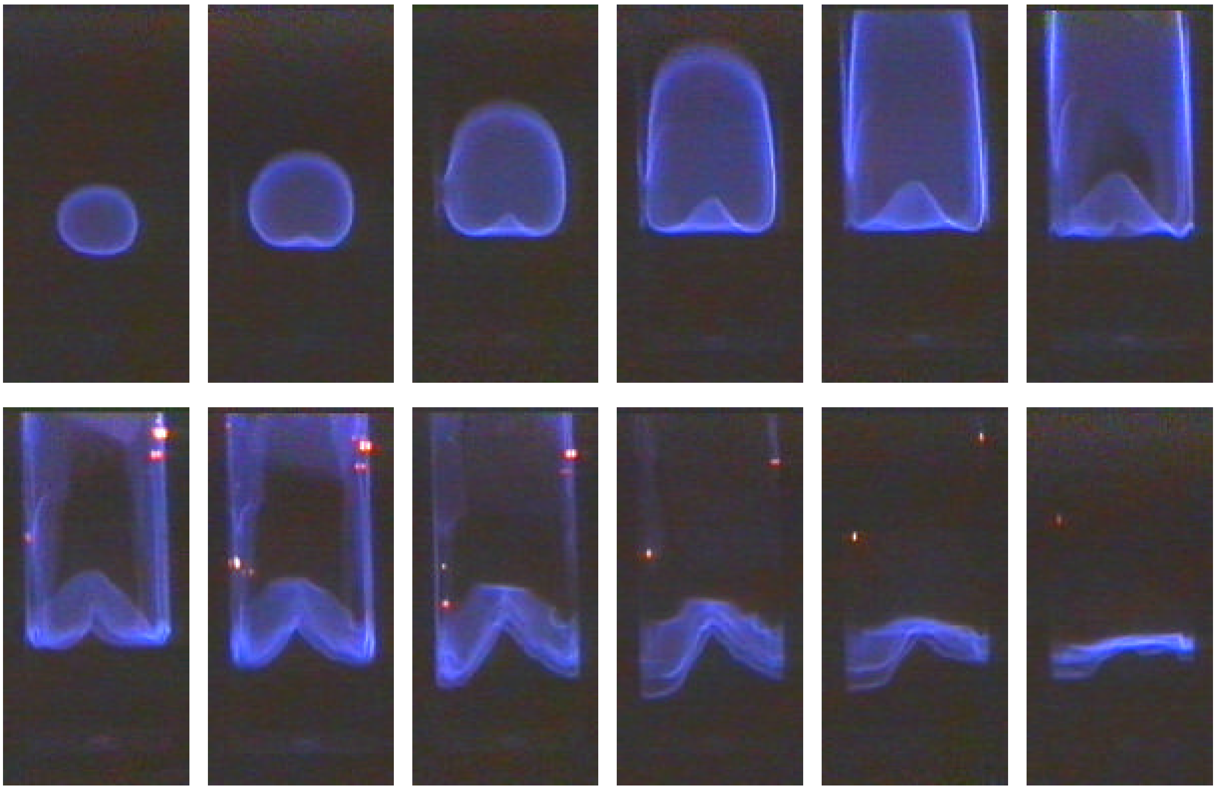

Fig. 4. Combustion developments from ignition to a plain downward propagating flames in a mixture 5.85% CH_4. Square tube 250mm × 250mm × 800mm. Time interval between frames 0.06 sec

The flame expanding to the corners pushes out the fresh mixture ahead of it to the inner space of the flame kernel – the inner cone that time temporarily increases. Just then the central part of the cone is occupied by very unstable downward propagating flame. The leaner is the mixture the faster the flame dies out. It was found out no difference in flammability limits for downward propagating flames for tubes under investigations. The extinction mechanism of a flame propagating in the limit mixture was always the same. The downward propagating limit flame first was quenched locally near the wall and then the quenching wave spread around, close to the walls surface (Fig.5). Just before extinction the flame occupied only the part area of the tube.

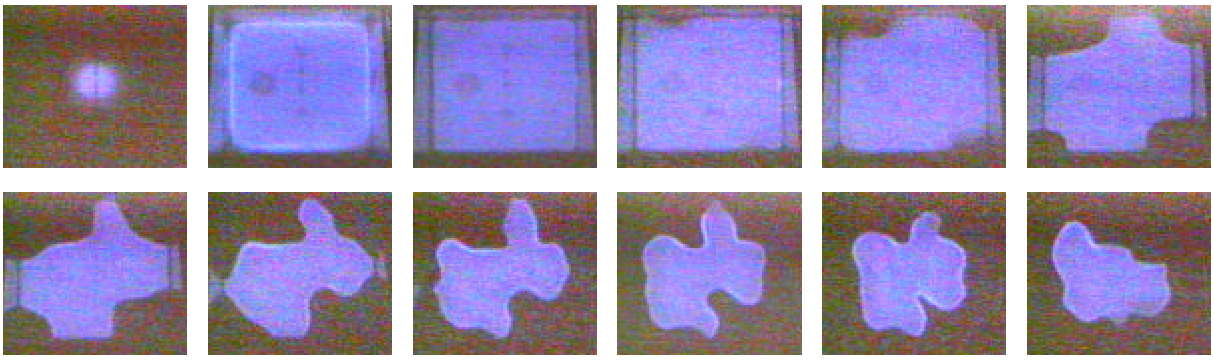

Fig. 5. Quenching process of a plain limit flame, propagating downward in 2.2 C_3H_8 mixture, observed in a mirror located at the bottom closed end of the tube. Square tube 125mm $\times$ 125mm $\times$ 500mm Time interval between frames 0.2 sec

Discussion

The flame propagating downward in non-limit mixture is always convex. The convex flame front exists in spite of stabilizing action of gravity. This indicates instability of the plane flame front. The convex surface of the flame may be treated as its curved cell, which has been formed after the plane flame, lost its stability [7]. The steady state of such flame is a result of the nonlinear hydrodynamic interaction with the gas flow field. For the convex flame the flame surface S can be determined from the relation $S = F\frac{u}{u_L}$, where F is cross-section surface of the tube, u is propagation velocity of the leading point and u_L is laminar burning velocity. It was found theoretically that flame convexity is a function of an expansion ratio $1/\alpha=\rho_0/\rho_b$, which depends on the equivalence ratio ϕ [7]. Decreased mixture concentration is followed by decreased flame convexity. For the limit mixture concentration the flame becomes flat and its propagation velocity is close to limit laminar burning velocity for downward propagating flames. Further reduction of mixture concentration would reduce laminar burning velocity below the limit value with following flame extinction near the wall. After some time the flame loses its contact with the tube walls and is floating freely in the central part of the tube. The residual flame with hot gases behind it is finally driven to extinction by differential buoyancy which forces cooler product gases ahead of the flame.

Very similar mechanism of flame extinction occurs in a quenching channel – also here the propagation velocity decreases below the limit laminar burning velocity. Cold walls in a narrow channel can quench every flame. The influence of a cold wall on flame quenching phenomena can be explained by the experimental data presented in [8]. Curve 1 in Fig. 6 represents the measured velocities of a downward propagating flame in quenching channel [8] and line 2 indicates the magnitude of the adiabatic laminar burning velocity. Experiments show that outside the limit conditions the flame is curved (according to [7] this curvature indicates that the flame is unstable) and propagates at a velocity which is higher than the laminar burning velocity. The displacement of a plane flame in a quenching channel is possible only in a very narrow range of conditions approaching the limit conditions. Because the limit flame is plain then further decreasing of plate separation reduces the laminar burning velocity below the limit magnitude and the flame dies out.

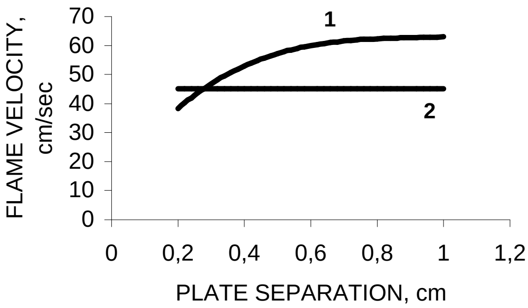

Fig. 6. Velocity of a downward propagating flame in stoichiometric methane/air mixture as a function of plate separation [8].

References

[1]. Coward H. F. and Jones G. N., “Limits of Flammability of Gases and Vapors”, U. S. Bureau of Mines Bull. 503, 1952.

[2]. Jarosinski J., Strehlow R. A. and Azarbarzin A., “The Mechanisms of Lean Limit Extinguishment of an Upward and Downward Propagating Flame in a Standard Flammability Tube”, Nineteenth Symposium (International) on Combustion, The Combustion Institute, pp. 1549-1557, 1982.

[3]. Strehlow R. A., Noe K. A. and Wherley B. L., “The Effect of Gravity on Premixed Flame Propagation and Extinction in a Vertical Standard Flammability Tube”, Twenty-First Symposium (International) on Combustion, The Combustion Institute, pp. 1899-1908, 1986.

[4]. Krivulin V. N., Lovachev L. A., Kudryavtsev E. A. and Baratov A. N., Fizika Gorenya y Vzryva, 11: 890, 1975.

[5]. Aly S. L. and Hermance C. E., “A Two-Dimensional Theory of Laminar Flame Quenching”, Combust. Flame, 40: 173-185, 1981.

[6] Daou J. and Rogg B., “Influence of Gravity on the Propagation of Initially Spherical Flames”, Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute, pp. 1275-1281, 1996.

[7]. Zeldovich Ya. B., Istratov A.G., Kidin N.I. and Librovich V. B., “Hydrodynamics and Stability of Curved Flame Front Propagating in Channels”, Institute for Problems in Mechanics, The U.S.S.R. Academy of Sciences, preprint nr 143, Moscow 1980.

[8]. Jarosinski J., “Flame Quenching by a Cold Wall”, Combust. Flame, 50: 167-175, 1983.