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Quenching Distance and Quenching Diameter Ratio for Flames Propagating In Propane/Air Mixtures

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Abstract **-** Flames in propane/air mixtures propagating in square d_s and circular d_c ducts of small sizes have been experimentally investigated. The flames propagated upwards and downwards from the open end of the duct to the closed one. An influence of the direction of flame propagation, cross-section and dimensions of the duct on the flame propagation velocity in the stoichiometric mixture has been determined. Experimental results have shown that the direction of flame propagation has an insignificant influence on the flame propagation velocity S_L, for both circular and square ducts. The shape of the duct also has an inconsiderable effect on the flame propagation velocity for duct sizes greater than 7 mm. For smaller values of these parameters, a flame propagation velocity difference is visible. This velocity is lower in square ducts than in the circular ones for the same characteristic size. Flame propagation velocities in the smallest ducts (d_s = 2.5 mm and d_c = 3 mm) are almost the same and are about 25 cm/s. The quenching distance (square duct) and the quenching diameter (circular duct) have been determined and compared. For lean mixtures, quenching distances and diameters are almost the same for downward and upward flame propagation. For rich mixtures, quenching limits for downward and upward propagating flames coincide up to Φ = 1.55, then these limits split up. The quenching diameter is greater than the quenching distance for mixtures with the equivalence ratio $\Phi \sim 0.6 \div 1.55$. The existence of this difference is probably caused by the dead space.

Keywords**:** Flame quenching, Quenching distance, Quenching diameter, Flame propagation.

1. Introduction

Flame quenching by the wall is important for understanding the combustion process near the wall. It is known that every flame can be quenched if the walls of the duct are placed close enough. A heat loss from the flame to the walls is responsible for this phenomenon.

The critical distance between flat plates, below which flame cannot propagate, is known as a quenching distance. However, a quenching diameter is generally used when a circular tube is used instead of flat plates.

The first extensive survey and analysis of quenching distance problems was made by Potter (1960). He discovered that the quenching distance depended on the fuel type, the mixture concentration and the direction of flame propagation. Later, the quenching distance and flame properties accompanying quenching conditions were studied for flames propagating in methane/air mixtures (Jarosinski, 1983) and further in propane/air mixtures (Jarosinski and Podfilipski, 2001). For flames in lean methane/air and rich propane/air mixtures (Le < 1), the quenching distance depends on the direction of flame propagation, upwards or downwards. Flame stretch and preferential diffusion are the physical factors responsible for the difference between two directions of propagation.

If we assume a plane flame propagating in the tube of the diameter d, the ratio of the heat loss surface A to the flame volume V within the flame thickness δ is $\pi d\delta/(\pi d^2\delta/4) = 4/d$. For a square duct of the width d, A/V is $4d\delta/(d^2\delta) = 4/d$. It can be seen that regardless of whether d is the diameter of the circular duct or the width of the square duct, the ratio A/V is the same and equal to $4/d$.

The aim of this work was to determine a relation between the quenching diameter (circular duct) and the quenching distance (square duct) for downward and upward propagating flames in propane/air mixtures.

2. Experimental Methodology

The experiments were conducted in several vertical, 300 mm long, square cross-section ducts with different widths (from 2.5 mm to 15 mm) and a circular cross-section (500 mm long) with different diameters (from 3 mm to 12.4 mm). A schematic view of the experimental stand is shown in Figure 1. The entire system can be rotated by 180 degrees, which allows one to observe the flame moving either in the direction of the gravity acceleration and in the opposite direction. The flow rates of propane and air were controlled by two separate mass flow controllers (MFC) with the accuracy of 1÷2%, depending on the flow rate value. The gases were mixed in a mixing tank and entered the experimental stand. Before the mixture was ignited, the apparatus was swept with the same mixture about 100 times. During downward flame propagation experiments, the top end of the duct remained open. The opposite configuration was during upward flame propagation. The device used for mixture ignition resembled a cigarette lighter and was located near the open end of the duct. Flame propagation in the ducts was recorded with Casio Exilim Pro EX-F1 and Nikon D70s digital cameras. Pictures obtained from the first of them were used to determine the flame propagation velocity. Pictures taken with the second camera were used to determine the geometrical parameters of the flames in square ducts.

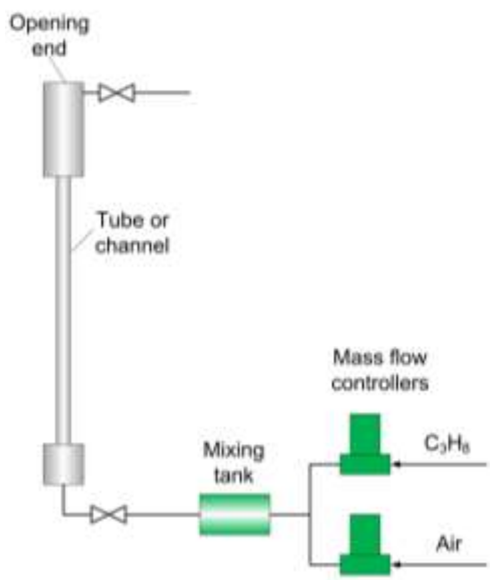

Fig. 1. Schematic view of the experimental stand.

To determine the quenching distance (square duct) and the quenching diameter (circular duct) for a given duct size, the limit mixture composition was gradually approached – up to the moment when the flame could no longer travel along the whole duct length. The dead space d_{ds} was determined from the pictures from the digital camera.

3. Results and Discussion

3. 1. Flames Propagating in a Stoichiometric Mixture

Experiments began with the flames propagation in a stoichiometric mixture in the widest of the ducts (15 mm – a square cross-section) and (12.4 mm – a circular cross-section). Then, their size was systematically reduced until the flame was not able to propagate in them. Measurements were performed for downward and upward flame propagation. The flame propagation velocities S_L as well as a function of the duct size and the direction of flame propagation are presented in Figure 2.

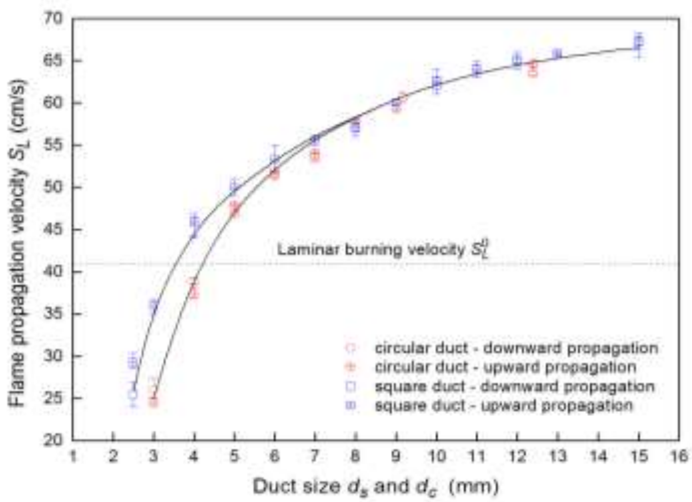

Fig. 2. Flame propagation velocity S_L as a function of the duct size for a stoichiometric mixture.

As shown in Figure 2, the direction of flame propagation has an insignificant influence on the flame propagation velocity S_L, for both circular and square ducts. The shape of the duct also has an inconsiderable effect on the flame propagation velocity for the duct size greater than 7 mm. For smaller values of these parameters, a flame propagation velocity difference is visible. This velocity is smaller in square ducts than in the circular ones for the same characteristic dimension.

Flame propagation velocities in the smallest ducts (d_s = 2.5 mm and d_c = 3 mm) are almost the same and are about 25 cm/s. However, for most ducts, the flame propagation velocity is greater than the laminar burning velocity S_L^o = 41 cm/s (Law (2006)). It is lower only for ducts slightly larger than the quenching distance $d_{s,q}$ and the quenching diameter $d_{c,q}$. The maximum value is for the duct d_s = 15 mm (67.5 cm/s). The factor responsible for an increase in velocity above the laminar burning velocity is a greater surface of the flames relative to the flat flame, which is used to determine S_L^o. In contrast, a decrease in S_L under S_L^o corresponds to a heat loss to the walls of the duct.

The cooling effect of the duct walls on the flame is visible for narrower ducts. This effect is shown in Figure 3 as a dependency of the dead space and the duct size ratio d_{ds}/d_s as a function of the duct size d_s.

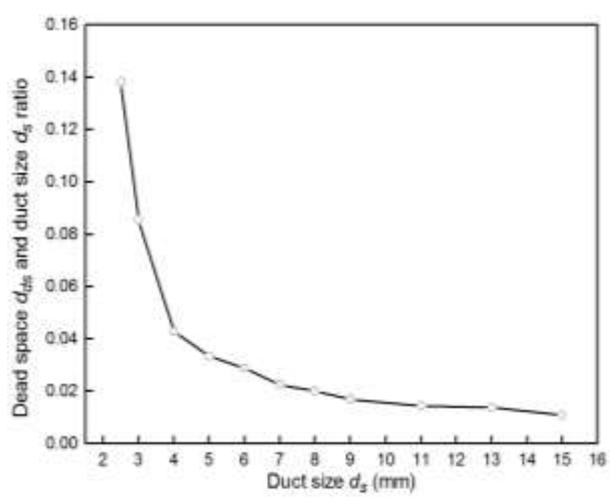

Fig. 3. Dead space d_{ds} and the duct size d_s ratio as a function of the duct size d_s.

The dead space and the duct size ratio increase slightly with the decreasing duct size up to d_s = 4 mm. For smaller ducts, this increase is more sharp and accompanied by a decrease in the laminar burning velocity and a possible lowering of the local temperature of a chemical reaction.

3. 2. Flames Propagating in Quenching Ducts

In the records from the digital camera, differences between the limit flames propagating downwards and upwards in lean and rich mixtures in d_s = 15 mm can be seen (Figure 4). The differences are in the flame color and in the extent of the dead space. Lean flames are blue, the rich ones show a greenish tint.

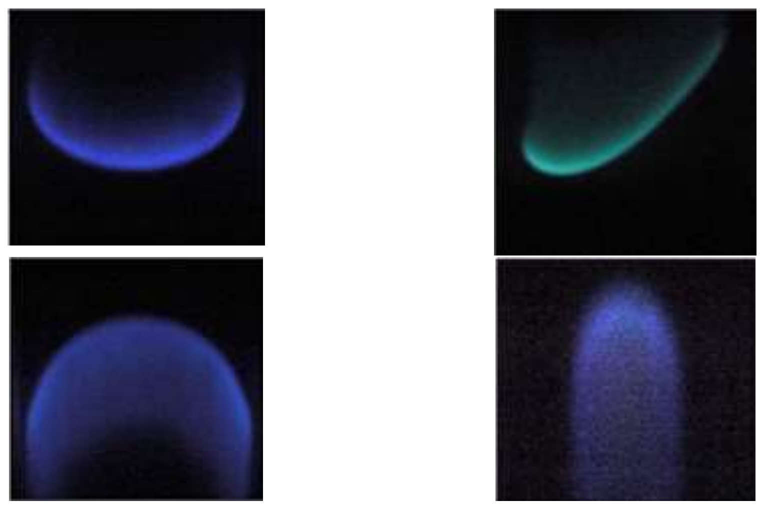

Fig. 4. Photos of the limit flames in lean and rich mixtures propagating downward and upwards in d_s = 15 mm.

The quenching distances $d_{s,q}$ and the diameters $d_{c,q}$ as a function of the mixture concentration are shown in Figure 5. One can see that for lean mixtures, the quenching distance and diameters are almost the same for downward and upward flame propagation.

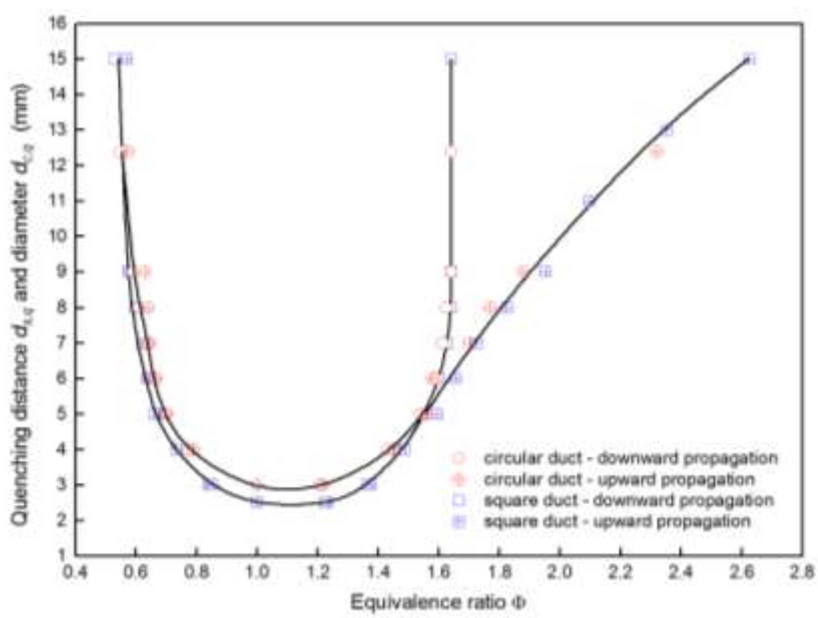

Fig. 5. Experimentally determined quenching distance $d_{s,q}$ and the diameter $d_{c,q}$ as a function of the equivalence ratio.

Surprising may be the fact that the downward propagating flame can move in leaner mixtures, whereas the upward propagating one cannot. This can be explained by a combined action of the Lewis number and the flame stretching. It also indicates the fact that the traditional method for determining the flammability limits proposed by Coward and Jones (1952) cannot be used for all cases.

For rich mixtures, the situation is quite different. Quenching limits for downward and upward propagating flames coincide up to Φ = 1.55, which corresponds to $d_{s,q} = d_{c,q}$ = 5 mm. For richer mixtures, flames propagating in the same ducts but in opposite directions are quenched at different mixture concentrations. The difference between downward and upward flame propagation limits rapidly increases with increasing Φ.

For rich mixtures, the downward and upward flammability limits are Φ = 1.64 and Φ = 2.62 respectively. Such a wide gap between flammability limits is due to the preferential diffusion deficient reactant (oxygen) in response to stretching upwards the propagating flame (for these flames, Le < 1).

Figure 5 shows an influence of the shape of the duct cross-section on the flame quenching limit for lean mixtures. For duct sizes larger than 9 mm – $d_{s,q} = d_{c,q}$. For narrower ones (≤ 9 mm), the quenching diameter $d_{c,q}$ is larger than the quenching distance $d_{s,q}$ for the same mixture.

This discrepancy for rich mixtures persists up to $d_{s,q} = d_{c,q}$ = 5 mm. For downward propagating flames in richer mixtures, quenching distances are equal to quenching diameters. There is no visible influence of the mixture concentration on the quenching limit for duct sizes ≥ 9 mm.

The existence of a difference between the quenching distance and the quenching diameter is probably caused by the dead space. It forms the corners without flame in square ducts. These corners play an important role during the flame passage from a larger to smaller duct, because flame quenching occurs there as a result of an intense heat loss to the duct walls. However, for steady flame propagation in the square duct, heat losses at these points are minimal. If this area is omitted during the determination of the *A*/*V* ratio, it turns out that this quotient is greater for circular ducts than for the square ones. This may be a reason why quenching diameters are greater than quenching distances for the same characteristic size *d*.

The ratio of the quenching distance and the quenching diameter is equal to 0.82÷0.88 for the equivalence ratio Φ = 0.6÷1.4. This value increases when mixture concentrations come near limit mixtures, due to the fact that the curves describing the quenching distance and diameters begin to approach each other.

The quenching distance (or diameter) is associated with parameters of the flammable mixture by the critical Peclet number:

$$Pe = \frac{S_L^0 d_q}{\alpha} \tag{1}$$

where α is the thermal diffusivity of the cold mixture and d_q is the quenching characteristic dimension of the duct.

It is widely accepted that the Peclet number is determined for downward propagating flames. Jarosinski et al. (2002) determined the critical Peclet number in the wedge-shaped channel, obtaining an almost constant value of 42. The values necessary for calculation of laminar burning velocities were taken from Vagelopoulos and Egolfopoulos (1998). The calculated critical Peclet number as a function of the equivalence ratio for circular and square ducts is presented in Figure 6.

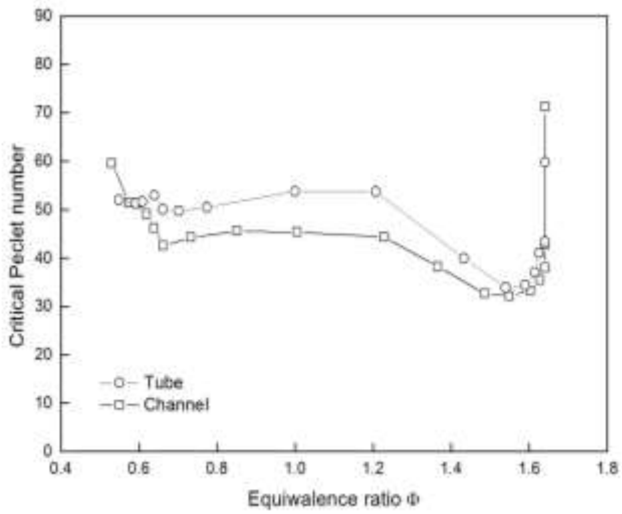

Fig. 6. Critical Peclet number as a function of the equivalence ratio and the cross-section duct.

For square ducts and in the range of the equivalence ratio Φ = 0.64÷1.23, we have *Pe* = 42.5÷45.5. It rises up to 59.5 for leaner mixtures, whereas for richer mixtures it first drops to 32 and then rises up to 71.

For circular ducts and in the range of the equivalence ratio Φ = 0.55÷1.2, the value of *Pe* = 51÷54. For richer mixtures, it decreases to 33 and then increases up to 60.

4. Conclusion

Detailed investigations of flame propagation in narrow ducts with different cross-sections were carried out for propane/air mixtures. The investigations of flames in the stoichiometric mixture showed that the direction of flame propagation had an insignificant influence on the flame propagation velocity S_L, for both circular and square ducts. The shape of the duct affects the flame propagation velocity for duct sizes narrower than 7 mm. For bigger ones, its influence can be negligible. The flame propagation velocity is lower in square cross-section ducts than in the circular ones for the same characteristic size *d*. Flame propagation velocities in the narrowest ducts (d_s = 2.5 mm and d_c = 3 mm) are almost the same and are equal to about 25 cm/s.

The quenching distance (square cross-section duct) and the quenching diameter (circular cross-section duct) have been determined and compared. For lean mixtures, quenching distances and diameters are almost the same for downward and upward flame propagation. For rich mixtures, quenching limits for downward and upward propagating flames coincide up to Φ = 1.55, then these limits split up. The quenching diameter is greater than the quenching distance for mixtures with the equivalence ratio Φ ~ 0.6÷1.55. The existence of this difference is probably caused by the dead space, which reduces the heat loss surface.

The critical Peclet numbers expressed by the quenching distance $d_{s,q}$ or the quenching diameter $d_{c,q}$ and the laminar burning velocity measured by Vagelopoulos and Egolfopoulos (1998) in a broad range of mixture compositions are almost constant and equal to 42.5÷45.5 and 51÷54 for square and circular ducts, respectively.

Acknowledgements

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References

Coward H.F. and Jones G.W. (1952). Limits of Flammability of Gases and Vapors. Bulletin 503, Bureau of Mines.

Jarosinski J. (1983). Flame Quenching by a Cold Wall. Combustion and Flame **50**, 167-175.

Jarosinski J. and Podfilipski J. (2001). Properties of Propane Flames. In: Eighteenth International Colloquium on the Dynamics of Explosions and Reactive Systems, pp. 90–94, Seattle.

Jarosinski J., Podfilipski J. and Fodemski T. (2002). Properties of Flames Propagating in Propane-Air Mixtures Near Flammability and Quenching Limits. Combustion Science and Technology **174**, 167–187.

Law C.K. (2006). Combustion Physics. Cambridge University Press, New York, USA.

Potter A.E.J. (1960). Flame Quenching. In: Progress in Combustion and Fuel Technology, Vol. 1 (ed M. G. a. A. H. L. J. Durcarme), J. Durcarme, M. Gerstain and A. H. Lefebvre edn, pp. 145-182. Pergamon Press.

Vagelopoulos C.M. and Egolfopoulos F.N. (1998). Direct Experimental Determination of Laminar Flame Speeds. 27th Symposium (International) on Combustion, 513-519.