Effect of propagation speed on the quenching of methane, propane and ethylene premixed flames between parallel flat plates

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Abstract

This paper reports on an experimental investigation of the effect of flame speed on the quenching distance. In a rectangular section channel, the quenching distance of methane-air, propane-air and ethylene-air flames, arriving on the quenching element with different speeds, is investigated. The experiments are performed in a constant volume combustion chamber comprising two volumes separated by the quenching section. The quenching tests are performed at pressure close to atmospheric, with an initial temperature of the walls and flammable mixture of 293 K. Flame quenching is assessed from pressure measurements, while the apparent flame speed is determined from fast schlieren imaging. The results show a similar trend for the three fuels considered: the quenching distance for laminar propagating flames is about twice smaller than when the flow becomes turbulent, close to the entrance of the channel. In the case of laminar flames, the quenching distance is almost

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constant at $1.3 - 1.5$ mm for the conditions considered, while for turbulent flames, depending on the fuel and equivalence ratio, the quenching distance is in the range $2 - 2.5$ mm. Starting from the quenching theory, the results are analyzed and the effects of flame curvature and turbulence are discussed.

Keywords: Flame arrester, tube quenching, flame stretch, turbulence quenching, heat transfer.

1. Introduction

Flame arresters are devices that are able to stop combustion in equipment and piping systems where flammable gases may be present [1]. They are applied widely for industrial and technical purposes but, unfortunately, as the flames are sensitive to numerous parameters, improving their efficiency and versatility is challenging. Passive flame arresters generally operate by flame quenching on surfaces. Depending on the conditions, this quenching may be due to thermal loss (heat transfer from the flame to the wall) and/or radical quenching (reaction of flame radicals at the wall surface) [2, 3, 4, 5].

One of the [simplest](#) model of passive flame arresters is a tube. In this case, the quenching of the flame can be characterized as *tube quenching*, as the total flame quenching may occur within the tube, if its diameter is sufficiently small [6]. Depending on the volumes and geometries, upstream and downstream of the quenching tube, as well as the location of the ignition source, for similar initial conditions of the flammable mixture, the pressure, temperature and flow at the entrance of the quenching tube can be drastically different [1]. Therefore, understanding the effect of these three parameters on tube quenching is of practical interest for securing flame quenching.

19 For tubes with circular section, the smallest diameter at which a flame can
 20 propagate through the tube corresponds to the quenching diameter. For non-
 21 circular sections, the quenching diameter might be defined by the hydraulic
 22 diameter but it is geometry dependent [7, 8, 9]. A more general approach is
 23 to consider the quenching of flames between parallel plates. In this case, the
 24 quenching distance, d_Q , can be defined as the minimal distance at which a
 25 flame can propagate between two infinite parallel flat plates [10].

26 The effect of pressure, P , on the quenching distance has been broadly
 27 investigated for various fuels and equivalence ratios (see for example [11, 12,
 28 13, 14, 9]). A simple power law of the form:

$$d_Q = d_Q^0 \cdot P^n, \quad (1)$$

29 where d_Q^0 is the quenching distance at atmospheric pressure and n is an ex-
 30 ponent dependent on the fuel and equivalence ratio, gives relatively good
 31 agreement with experimental results [13]. For any hydrocarbon–air stoichio-
 32 metric mixtures, n is in the range -0.93 to -0.85 , while for stoichiometric
 33 hydrogen–air mixtures $n = -1.138$.

34 Studies of the effect of gas temperature on the quenching distance are
 35 generally associated with changes in the wall temperature [11, 15, 16], as it
 36 is relatively difficult to decouple the temperature of the gas and the wall,
 37 for distances in the range of d_Q . For temperatures between 293 and 500 K,
 38 the quenching distance is not significantly affected by the temperature and it
 39 has been shown that the main mechanism of flame quenching is heat transfer
 40 to the wall [17, 18, 16, 19]. Above 500 K, the quenching distance decreases
 41 drastically with temperature, and surface reactions start to become signifi-
 42 cant. The quenching distance is then affected by both the temperature and

43 the properties of the surface [20, 16].

44 Finally, the effect of flow on the quenching distance can be large, as
45 it impacts both the flame properties and the heat transfer to the wall [6].
46 However, studies focusing on this effect are scarce. The vast majority of
47 quenching distances available in the literature have been measured for slow
48 flows. Typically, for flows that are generated by the propagation of a flame
49 in a quiescent environment, *i.e.*, up to a few meters per second. However,
50 for applications related to flame arresters, these slow flows are encountered
51 for specific conditions only, such as when the ignition source is located close
52 to the quenching element.

53 By changing the fuel, the flame speed and the induced flow can be
54 changed, along with a change in the quenching distance [21]. However, for a
55 given flammable mixture, changes in the flow can also affect the quenching
56 distance. For example, an increase in speed of a laminar flow can induce
57 two mechanisms: a decrease in the local heat transfer rate to the wall and
58 a stretching of the flame front. Depending on the Lewis number of the mix-
59 ture, Le , these mechanisms can couple and the quenching distance decreases,
60 or compete and their effect on the quenching distance is more difficult to
61 predict. If the flow becomes turbulent, the effect on the quenching distance
62 can be even more dramatic. A few papers report on quenching studies in
63 turbulent flows [22, 23, 24, 25, 26], and even less on the effect of turbulent
64 flow on quenching distances [27, 28]. These conditions are of practical inter-
65 est because they correspond to cases of an ignition source far from the flame
66 arrester.

67 In [27, 28], Iida *et al.* investigated the behavior of turbulent propane–air

68 flames in narrow channels, at atmospheric pressure. They found that the
69 limit condition at which no flame will pass through a rectangular channel
70 depends only on the channel width (*i.e.*, the quenching distance), and not
71 on the inflow velocity or the radius of curvature of the path entrance. For
72 example, they measured a quenching distance of about 2 mm for turbulent
73 propane–air flames with an equivalence ratio of 0.8, regardless of the speed
74 of the flow. This value is close to the quenching distance for quiescent en-
75 vironment, 2.5 mm, as reported by Potter *et al.* in [13]. Therefore, it would
76 be tempting to consider that the quenching distance of propane–air flames
77 with 0.8-equivalence ratio ranges from 2.5 to 2 mm for laminar and turbulent
78 conditions.

79 However, recently, Biswas *et al.* investigated the effect of flow, from lam-
80 inar to turbulent, on the behavior of methane–air flames in a cylindrical
81 micro-tube of 100 mm length [26]. They showed that, while laminar stoichio-
82 metric flames could pass through a tube of 1 mm diameter, turbulent flames
83 were extinguished. As the geometry of the tube was changed in order to
84 accelerate the flow and reach turbulent conditions, and as only large incre-
85 ments of the tube diameter were investigated, from this study it is difficult
86 to quantify the effect of the transition from laminar to turbulence on flame
87 quenching. However, this study showed that knowing the quenching distance
88 for turbulent and quiescent conditions is not enough to predict the quenching
89 distance for all flow conditions.

90 To the best of our knowledge, the effect of flow, covering a large range
91 of velocities from laminar to turbulent, on the quenching distance of gaseous
92 flammable mixture has not been investigated, yet. This is the purpose of

the present study. In the context of flame arresters, the main objective is to identify the worst flow conditions to extinguish a flame. The second objective is to assess if the effect of flow on the quenching distance is fuel dependent.

Note that under particular circumstances, the turbulent flame might turn into a detonation. This aspect is not investigated here.

2. Experimental setup and procedure

In order to investigate the effect of flow on the quenching distance of flammable gas mixtures, a versatile constant-volume combustion chamber has been designed. The main specificity of this setup is that the velocity in the quenching section can be varied from laminar to turbulent, independently of the composition of the mixture. The experimental setup and the diagnostics used, as well as the procedure followed, are presented here.

2.1. Experimental setup

The experimental setup used in this study is presented in Fig. 1. It consists of a constant-volume combustion chamber that mimics the installation of a flame arrester between two tanks.

Upstream of the quenching section, a spherical vessel of about 5-L (Kimball Physics MCF600-SphCube-F6C8), is equipped with a gas inlet valve, an ignition system and a piezoelectric pressure transducer (Kistler Type 6001), connected to an amplifier (Kistler Type 5018A1000). The ignition is obtained with a spark of 1 ms duration, produced by applying a high-voltage pulse of 8 kV between two pin electrodes separated by 1.5 mm. The electrical energy deposited is about 20 mJ. The electrodes are located on the axis of the combustion chamber, 75 mm upstream the entrance of the quenching

Figure 1: a) Picture of the constant volume combustion cell, with b) the corresponding schematic, and c) a close look at the quenching section.

117 section. This value has been chosen as a good compromise between a large
 118 radius of curvature of the flame and a minimal increase in the pressure, when
 119 the flame reaches the quenching section. All the measurements have been
 120 conducted for an absolute pressure in between 1.06 and 1.10 bar, when the
 121 flame enters the quenching section.

122 The quenching section (see Fig. 1c), is a rectangular channel of 70-mm
 123 depth and 100-mm length, with a variable height, H . The depth of the chan-
 124 nel has been chosen large enough in order to not affect the measurement of
 125 quenching distances [21]. The quenching distance, d_Q , corresponds then to
 126 the smallest distance at which a flame can propagate through the quenching

127 section. Above and below the quenching section, the gas can flow but the
 128 flame cannot propagate, due to the presence of two quenching meshes (en-
 129 tangled metallic mesh). The thickness of the quenching elements, B , can be
 130 adjusted, independently from H . When the flame expand in the upstream
 131 vessel, fresh gases are pushed towards the downstream vessel, through the
 132 quenching section and the quenching meshes. For a given mixture, when
 133 the flame reaches the quenching section, the flow speed in the quenching
 134 section depends on the dimensions of the passage between the two vessels.
 135 Therefore, for a constant H , increasing B will increase the flow speed in the
 136 quenching section, and vice versa. Thus, the apparent flame speed, S_{fl} , in the
 137 quenching section can be varied by adjusting B . For small B (the minimal
 138 value is 3 mm), S_{fl} at the entrance of the quenching section is of the order
 139 of 10 m/s. By increasing B , the section of the upper and lower passages de-
 140 creases, and S_{fl} increases, up to 85 m/s. The total height of the test section
 141 that comprises the quenching section, the two quenching elements and the
 142 two auxiliary passages (quenching meshes) is equal to 60 mm. The quenching
 143 elements are made of aluminum. The edges are sharp from machining, *i.e.*,
 144 with a radius of curvature smaller than $50\text{ }\mu\text{m}$. Large optical access allows
 145 the visualization of the entire quenching section.

146 Downstream of the quenching section, a spherical vessel of 2.85-L (Kim-
 147 ball Physics MCF600-SphSq-F2E4A4) is equipped with a gas valve outlet.
 148 Note that the pressure in the downstream vessel is not regulated and it will
 149 naturally increase with the propagation of a flame from the ignition source.

150 *2.2. Diagnostics*

151 Quenching of the flame is assessed from dynamic pressure measurements
 152 obtained with the piezoelectric pressure transducer located in the upstream
 153 volume. Examples of pressure traces corresponding to successful and unsuc-
 154 cessful quenching events are presented in Fig. 2, for a stoichiometric methane–
 155 air mixture, with an apparent flame speed at the entrance of the quenching
 156 section of 20 m/s.

Figure 2: Examples of temporal evolution of the pressure in the combustion chamber, obtained for stoichiometric methane–air flames, $S_{fl} = 20$ m/s.

157 In this case, for $H = 1.3$ mm, the flame is not quenched and the maximal
 158 pressure reaches 6 bar, about 60 ms after ignition. For $H = 1.2$ mm, the
 159 flame is quenched and the maximal pressure barely reaches 4 bar, 125 ms
 160 after ignition. Note that the pressure trace during quenching event does not
 161 exhibit any oscillations, as it could be expected for a near limit phenomenon.
 162 This can be explained by the fact that only a small part of the flame is
 163 quenched in the quenching section, while the main flame in the upstream
 164 vessel is not affected. Therefore, even if locally the flame oscillates, the

165 induced pressure oscillations would be negligible compared to the pressure
 166 increase due to the flame propagation in the upstream vessel.

Figure 3: Sequences of schlieren images of stoichiometric methane–air flames obtained for: a) an apparent flame speed of 20 m/s and a channel height of 1.4 mm, b) an apparent flame speed of 54 m/s and a channel height of 1.8 mm, and c) an apparent flame speed of 80 m/s and a channel height of 2.4 mm. The frame rate of the camera is 15,000 fps.

167 The apparent flame speed, S_{fl} , is obtained by fast schlieren visualization
 168 of the quenching section. The light source is a continuous white LED. The
 169 camera is a C-MOS camera (Photron Fastcam Ultima APX), set with a frame
 170 rate of 15,000 fps. Examples of stoichiometric methane–air flames propagat-
 171 ing in the quenching section at 20, 54 and 80 m/s are presented in Figs. 3a,
 172 3b and 3c, respectively. These propagation speeds have been obtained by

173 adjusting B , from 3 mm for $S_{fl} = 20$ m/s, to about 29 mm for $S_{fl} = 80$ m/s.
174 From these images, S_{fl} is determined by considering the distance between
175 the right edge of the schlieren front at the entrance of the quenching section
176 (first row of Fig. 3), and on the image taken 1.06 ms afterward (last row of
177 Fig. 3).

178 Note that for $H < d_Q$, the flame does not propagate in the quenching
179 section. However the schlieren images are very similar to those with a propa-
180 gating flame. Indeed, as the flame continues to burn in the upstream vessel,
181 the hot products of combustion are pushed in the quenching section, inde-
182 pendently of the local extinction of the flame. Therefore, these images could
183 not be used to distinguish between successful and unsuccessful quenching
184 events.

185 A delay generator (Berkeley Nucleonics, model 575), synchronizes the
186 ignition with the pressure and schlieren measurement systems.

187 2.3. Procedure

188 First, the quenching section is setup (dimensions H and B are adjusted).
189 Then, the constant-volume combustion chamber is purged down to 5 mbar,
190 by using a vacuum pump (Edwards RV8). Afterwards, the chamber is filled
191 at 1.0 bar with a mixture of fuel and air at the desired equivalence ratio,
192 ϕ . The mixture is prepared in advance by the partial pressure method and
193 stored in a high-pressure cylinder (not shown in Fig. 1). After the mixture
194 reaches quiescent conditions, *i.e.*, after 1 min, it is ignited by the spark.
195 Pressure traces and images are recorded. For each experimental condition,
196 this procedure is repeated at least 5 times. The quenching distance, d_Q , is
197 taken equal to the minimal height at which at least one of the quenching

198 tests fails.

199 In order to identify the sensibility of the results to the fuel, four ex-
 200 perimental conditions have been tested. For all the conditions, the initial
 201 temperature and pressure are taken equal to ambient (293 K and 1 bar), but
 202 the fuel and equivalence ratios are changed. A summary of these experimen-
 203 tal conditions is displayed in Table 1. The corresponding adiabatic flame
 204 temperature, T_{ad} , Lewis number, Le, laminar burning velocity, S_L , and flame
 205 Blint thickness, δ_L^b , are also reported.

Table 1: Summary of the experimental conditions and associated adiabatic flame temper-
 ature, Lewis number, laminar flame speed and flame Blint thickness. The laminar flame
 speeds are taken from the literature and the flame Blint thickness calculated with Eq.4.

Fuel	ϕ	T_{ad} (K)	Le	S_L (m/s)	δ_L^b (mm)
CH ₄	0.8	1997	0.96	0.24 [29]	0.63
	1	2225	0.96	0.37 [29]	0.52
C ₃ H ₈	0.8	2042	1.88	0.30 [29]	0.53
C ₂ H ₄	0.6	1807	1.35	0.26 [30]	0.58

206 3. Results

207 3.1. *Flames in the quenching section*

208 From schlieren images, the apparent flame speed in the quenching sec-
 209 tion can be determined. Figure 4 presents examples of its evolution in the
 210 quenching section, for stoichiometric methane–air mixtures. The filled sym-
 211 bols correspond to cases for which quenching is obtained, while the empty

212 symbols correspond to cases for which there is no quenching. The error bars
 213 correspond to the uncertainty in the velocity determination, based on the
 spatial resolution of the schlieren images.

Figure 4: Examples of the evolution of the apparent flame speed in the quenching section for stoichiometric methane-air flames.

214
 215 For slow flames ($S_{fl} = 20$ m/s), first the apparent flame speed increases,
 216 up to 27 m/s at 14 mm from the entrance of the quenching section. Then, it
 217 continuously decreases, down to 16 m/s at 90 mm from the entrance of the
 218 quenching section. The average Reynolds number with respect to the fresh
 219 gases is about 1,500. As in addition, the flame front does not display any
 220 wrinkling (see Fig. 3a), the flame can be considered as laminar. If quenching
 221 happens (filled symbols), the velocity of the schlieren front is slightly lower
 222 than when the flame is not quenched, but the trend remains the same. This
 223 similar evolution suggests that the flow dynamics in the quenching section is
 224 mainly controlled by the flame propagation in the upstream vessel.

225 For fast flames ($S_{fl} = 80$ m/s), the apparent flame speed monotonically
 226 increases up to 117 m/s at 86 mm from the entrance of the quenching section.

227 The average Reynolds number with respect to the fresh gases is about 15,000.
 228 As in addition, the flame front is wrinkled (see Fig. 3c), the flame can be
 229 considered as turbulent. If quenching happens (filled symbols), during the
 230 first half of the quenching section (50 mm), the velocity of the schlieren front
 231 is slightly lower than when the flame is not quenched. In the second half
 232 of the quenching section, the velocity seems to stabilize at about 100 m/s.
 233 Therefore, for turbulent cases, the dynamics of the flow in the quenching
 234 section seems to be influenced by both the part of flame in the upstream
 235 vessel and the part of the flame in the quenching section.

Figure 5: Examples of the evolution of the apparent flame speed in the quenching section for the four mixtures considered in this study. For all these conditions, no quenching is obtained.

236 It is interesting to note that no tulip flame behavior (oscillations of the
 237 apparent flame speed of flames propagating in ducts) can be observed, like
 238 for example in [31, 32]. This can be explained by the fact that in the present
 239 study, when the velocity measurements are taken, the main part of the flame
 240 is not in the channel but in the upstream vessel. Therefore, the dynamics

of the flame portion in the quenching section is not representative of the interaction of a flame front with its self-generated flow in an enclosure.

These trends are similar for all the experimental conditions summarized in Table 1. For clarity reasons, Fig. 5 presents only examples of the evolution of the apparent flame speed in the quenching section for cases for which no quenching is obtained.

3.2. Stoichiometric methane–air flames

Figure 6 presents the quenching distance, d_Q , of stoichiometric methane–air flames as a function of the apparent flame speed, S_{fl} , at the entrance of the quenching section. The uncertainty in the measurement of H is reported as error bars in Figs. 6 and 7. For slow flames, up to 40 m/s, the quenching distance is constant at 1.3 mm. For fast flames, above 60 m/s, d_Q is also almost constant, but at a larger value of 2.3 mm. In between, it sharply rises from 1.3 to 2.3 mm.

Figure 6: Quenching distance of stoichiometric methane–air flames as a function of the apparent flame speed at the entrance of the quenching section.

255 Compared with the schlieren images presented in Fig. 3, it is interesting
 256 to note that for $S_{fl} = 20$ m/s (Fig. 3a), the flame is laminar. The correspond-
 257 ing quenching distance is $d_Q = 1.3$ mm. For $S_{fl} = 80$ m/s (Fig. 3c), shortly
 258 after the entrance of the quenching section, the flame becomes turbulent.
 259 The corresponding quenching distance is $d_Q = 2.3$ mm. For $S_{fl} = 54$ m/s
 260 (Fig. 3b), at the entrance of the quenching section, the flame is laminar, but
 261 after 0.5 ms, wrinkling appears and it becomes turbulent. The quenching dis-
 262 tance is then in between those obtained for laminar and turbulent conditions:
 263 $d_Q = 1.8$ mm.

264 3.3. Effects of fuel and equivalence ratio

Figure 7: Quenching distance as a function of the apparent flame speed at the entrance of the quenching section for all the flames investigated in this study.

265 The influence of the apparent flame speed on the quenching distance
 266 has been investigated for all the conditions displayed in Table 1. Figure 7
 267 presents the results obtained. For all conditions investigated, the quenching
 268 distance of laminar flames is in the range 1.3 to 1.5 mm. At the transition

269 from laminar to turbulent, the quenching distance rises sharply, similarly
 270 to what has been obtained for stoichiometric methane–air flames. Thus, the
 271 effect of the flow on quenching between two parallel plates seems to be similar
 272 for flames with Lewis number close to and larger than unity.

273 In [27], the quenching distance for turbulent propane–air flames with 0.8
 274 equivalence ratio is about 2 mm, and one of the main conclusions is that the
 275 quenching distance is independent of the flow velocity. The results obtained
 276 in the present study are in agreement with [27], for turbulent flows only.
 277 On the other hand, the results presented in Fig. 7 shows that if the flow is
 278 not turbulent but laminar, then the quenching distance becomes significantly
 279 smaller (1.3 to 1.5 mm for laminar flames, compared to 2.1 mm for turbulent
 280 flames).

281 4. Discussion

282 Williams [10] expresses the quenching distance, d_Q , for a flame propagat-
 283 ing in a quiescent mixture, as a function of the flame diffusive thickness, δ ,
 284 or as a function of the laminar burning velocity, S_L , as:

$$d_Q = \text{Pe} \cdot \delta = \text{Pe} \cdot \frac{\lambda}{c_p \rho S_L}, \quad (2)$$

285 where Pe is the Péclet number at quenching, λ is the thermal conductivity, c_p
 286 is the specific heat at constant pressure, and ρ is the density of the unburnt
 287 gases. This model gives good agreement with experimental results obtained
 288 for flames propagating in quiescent environments quenched by cold surfaces.
 289 However, for more complex configurations, such as flame–flow–wall interac-
 290 tions, Eq. 2 may fail. Indeed, as the Péclet number can be expressed as the

product of the Reynolds number, Re , and the Prandtl number, Pr [33], Eq. 2 would give a linear increase in d_Q with an increase in the flow velocity. This trend is not observed in the present study (see Figs. 6 and 7). Furthermore, the stretch effects are not accounted for in Eq. 2.

More recently, Boust *et al.* [19], have shown that for head-on and side-wall quenching of flames propagating in a quiescent environment, the distance at quenching, d_q , and the heat flux to the wall, Q_w , are related by:

$$\frac{Q_\Sigma}{Q_w} = Pe + 1 = \frac{d_q}{\delta} + 1, \quad (3)$$

where Q_Σ is the flame power. Thus, at quenching, for a similar flame power, decreasing d_q increases the heat flux to the wall and vice versa. However, in the case of quenching between parallel plates, the quenching process can be more complex as it involves both, heat loss to the wall and curvature of the flame front. The curvature effect is not taken into account in this model.

4.1. Quenching of laminar flames

Figure 8 compares the quenching distances obtained in this study for the slowest flames (filled symbols), with results from the literature (empty symbols). The experimental configurations of the previous studies are different, complicating direct comparisons, however, in all cases, the quenching distances are taken as the minimal distance at which a flame could propagate between parallel flat plates and the flame propagation speeds are very slow, less than a few meters per second (quiescent environment or laminar burners). The quenching distances measured in the present study, with S_{fl} ranging from 10 to 20 m/s, are significantly lower than those obtained from the literature for slow flames. On the other hand, they are larger than twice

Figure 8: Quenching distance as a function of fuel and equivalence ratio. Comparisons between data from literature [13, 7, 34, 35] and results from this study obtained for the slowest velocities.

the distance of quenching obtained for side-wall quenching. For example, for stoichiometric methane-air flames, the quenching distance measured in this study for $S_{fl} = 20$ m/s is $d_Q = 1.3$ mm. It is twice smaller than the quenching distance measured for quiescent mixture (2.5 mm, [7]), and twice larger than two times the distance measured for side-wall quenching (2×0.3 mm, [19]). This result might be explained by considering the quenching processes between parallel plates.

Consider a flame propagating between two parallel flat plates separated by a large distance ($H \gg d_Q$). Close to each plate, the flame is locally quenched (side-wall quenching) but this local quenching does not globally extinguish the flame. If H is decreased, the curvature of the flame front is increased while the side-wall quenching is minimally affected. For small enough H , the curvature effect at the tip of the flame starts to play a role on the combustion process. For flames with a Lewis number larger than unity,

the flame is then weakened, and extinction at the tip of the flame can occur, eventually leading to a global extinction of the flame. In the present study, the quenching of all laminar flames happens when the radius of curvature of the flame tip is about 0.6 mm, *i.e.*, slightly smaller than $H/2$ at quenching. The radius of curvature of the flame is then of the same order of magnitude than its thermal thickness (see Table 1), that can be approximated by the Blint thickness, δ_L^b , defined as [36]:

$$\delta_L^b = 2\delta \left(\frac{T_2}{T_1} \right)^{0.7}, \quad (4)$$

where T_1 is the fresh gases temperature (293 K), and T_2 is the burnt gases temperature (here taken equal to the adiabatic flame temperature). Therefore, the curvature effect is likely to play a significant role on the flame quenching.

For lean and stoichiometric methane–air flames, as the Lewis number is equal to 0.96, the curvature effect should slightly enhance the combustion, instead of weakening it. However, the quenching distance is similar than for conditions with Lewis number larger than unity (more than twice the distance of side–wall quenching). In [16], Kim *et al.* obtained a similar result for the quenching of slow methane–air flames between parallel flat plates. They explained this result by the fact that the flame is not adiabatic in such a confined environment.

Thus, for flames with $Le \geq 1$, the quenching process between parallel flat plates involves both heat loss to the walls and the stretch effect by curvature. As reported in the literature [4], d_Q is then always larger than the sum of the two side–wall quenching distances. For lean and stoichiometric hydrogen–air

351 flames, the curvature effect is *opposite* and d_Q should be closer to twice the
352 side-wall quenching distance.

353 Finally, as shown in Fig. 7, d_Q is almost constant for all the laminar
354 conditions, regardless of the fuel and the apparent flame speed. This result
355 is surprising if only heat losses to the wall are considered. Indeed, as the
356 propagation time in the quenching section is larger for slow flames, then it
357 would have been expected that the quenching distance would have been larger
358 for slow flames. This is not observed in the current study, with apparent flame
359 speeds varying from 10 to 40 m/s. Note that increasing S_{fl} does not increase
360 the aerodynamic stretch of the flame. Indeed, S_{fl} is the propagation speed of
361 the flame compared to the wall and not the displacement speed of the flame
362 compared to the fresh gases. In the present experimental configuration, the
363 flame propagates into fresh gases, that are “pushed” in the downstream vessel
364 by the expansion of hot products in the upstream vessel. For a given mixture,
365 even if S_{fl} is changed, the flame displacement speed and consequently the
366 aerodynamic stretch remain unchanged. Consequently, the almost constant
367 d_Q measured for all the laminar flames could be explained only by a coupling
368 between heat loss to the wall and curvature effects. Further investigation
369 will be necessary to determine which of this effect is dominant.

370 4.2. *Quenching of turbulent flames*

371 For turbulent flows, the quenching distances are between 45 and 85%
372 larger than those measured for laminar flows (see Fig. 7). They are similar
373 to those reported in the literature for turbulent flames [27, 26]. This sharp
374 increase in d_Q at the transition from laminar to turbulent may be explained
375 by a change in the quenching process.

376 At the entrance of the quenching section, for all the cases investigated
377 the flames are laminar. Then, for flames with an apparent flame speed larger
378 than 40 m/s, the flame becomes turbulent in a few centimeters (see Fig. 3).
379 The turbulence can contribute to the weakening of a flame by three main
380 ways: i) by increasing the flame stretch, ii) by enhancing the heat transfer
381 to the wall, and iii) by turbulence mixing of the flame front with the fresh
382 gases, as suggested in [27]. Therefore, when a flame becomes turbulent it can
383 be quenched for larger distances between two plates than a laminar flame of
384 the same mixture.

385 Similarly to what is obtained for laminar flames, the quenching distance
386 of turbulent flames is not strongly sensitive to the fuel and the velocity. This
387 minimal impact of the velocity was also reported in [27]. However, the range
388 of turbulence levels investigated is relatively small. Further investigation
389 with larger range of turbulence levels will be necessary to conclude.

390 5. Conclusion

391 This experimental investigation of the effect of flow on the quenching dis-
392 tance of methane, propane and ethylene premixed flames shows that the
393 worst conditions for flame quenching correspond to laminar flows. The
394 quenching distances reported in the literature could be more than twice
395 larger than the minimal distance at which a laminar flame can propagate
396 between two parallel plates, without being quenched. Laminar flames are
397 more difficult to quench than both turbulent flames and flames propagating
398 in quiescent environments.

399 When the flow transitions from laminar to turbulent, the quenching dis-

400 tance is significantly increased, up to 85%. The proposed explanation for
401 this result lies in a change in the quenching processes. In addition to the
402 heat loss to the wall, for laminar flames, stretch induced by curvature due to
403 flame confinement could control the quenching process, while for turbulent
404 flows turbulence quenching seems to be the dominant mechanism.

405 For turbulent flames, the quenching distance is minimally affected by
406 the flow velocity. This result is in agreement with what was obtained for
407 propane–air flames in [27].

408 Finally, as the results are similar for all cases considered, this study sug-
409 gests that for Lewis numbers close to or larger than unity, the effect of Lewis
410 number on the quenching distance of laminar and turbulent flames is mini-
411 mal, compared to the effect of flow regime.

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