

ENC-2020-0385

## STATE OF THE ART ON QUENCHING DISTANCE STUDIES

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**Abstract.** *Quenching distance is a measure necessary to understand how premixed flames extinguish and to assist on the design of flame arresters. The present work aims to present the state of the art on quenching distance studies. The available theoretical model is presented with the simplified considerations to determine the quenching distance between two parallel plates. Experimental data agree with theory presented on a flame quenching by a cold wall. Temperature and pressure increases cause the quenching distance to decrease. Equivalence ratio also affects quenching distance, stoichiometric mixture provides the minimum quenching distance. The dimensionless parameter  $b$  for the quenching distance model is calculated with experimental data. In numerical modelling, detailed mechanism demonstrates better results than global mechanism because detailed mechanism predicted the flame quenching. Empirical models for temperature, pressure and flame speed are presented to predict quenching distance.*

**Keywords:** *Quenching distance, quenching flame, review.*

### **1. INTRODUCTION**

Power plants aim to high combustion efficiency to convert the energy from fuels to work. Turbines operate with fewer emissions when premixed flames are employed (Nemitallah; Abdelhafez; Habib, 2020). Although, there is a higher risk of accidents when premixed flames are used because flashback may occur in the upstream pipeline causing a deflagration or even a detonation inside pipelines. In petrochemical industry, many processes transport flammable species in pipelines. The risk of accidents is high due to temperatures and pressures involved. Explosions and fire are statistically the main accidents in oil refineries (Chettouh; Hamzi; Benaroua, 2016).

Quenching distance is a flame characteristic that depends on temperature, pressure, fuel, and mixture compound. Quenching distance can be defined as the minimum distance that a flame is able to propagate inside a channel or even the minimum diameter for a tube. This length is a necessary variable in flame arrester engineering projects.

In order to enhance process safety during the operation of those plants it is necessary to develop devices such as flame arresters. Flame arresters promote the heat loss from the flame, forcing the flame to quench. Heat loss is capable to reduce the rate of the chemical reactions, inducing the extinction of the flame. Flame arresters should ideally cause the minimum friction losses in the flow to keep an efficient and safety process in the industry. Quenching distance is a measure necessary to understand how flames extinguish and to assist on the design of flame arresters.

Although flame quenching is a common phenomenon related to the propagation of premixed flames, the combustion literature still lacks an up to date literature review that explains the different aspects related to the flame quenching phenomenon. The present work aims to perform such a literature review on quenching distance in order to establish the state of the art on this subject. The article is organized to show four aspects, namely, theoretical developments, experimental determination, numerical modelling, and correlation models. There are at least three models for quenching distance and we will focus on the quenching distance by a cold wall.

## 2. STATE OF ART ON QUENCHING DISTANCE

### 2.1 Theoretical Model

Quenching distance ( $d_q$ ) is defined as the minimum distance through which a premixed flame can propagate. For example, if the flame is propagating inside a tube, the quenching distance would be the minimum diameter that allows flame propagation. For a flame that is propagating inside a channel, being its height considerably smaller than its width, the quenching distance would be the minimum height that allows for flame propagation. There are some models and experiments used to determinate this variable.

Head on quenching is a technique that measures the quenching distance where the flame propagates perpendicular to the wall. On the other hand, sidewall quenching is a technique where the flame propagates parallel to the wall (Kalantari; McDonnell, 2017). Both techniques are important in combustion studies, it is necessary to emphasize their application in combustion chambers with characteristic lengths  $L \gg d_q$ . This work will follow the definition of quenching distance according to the model presented in section 2.2.1 which is relevant to design flame arrester because the characteristic length is  $L \sim d_q$ .

#### 2.1.1 Quenching by cold wall

Theoretical models express the quenching distance using simplified analysis. Quenching by a cold wall is a model that considers a laminar premixed flame propagating through a slot of two plane-parallel plates. According to this model, quenching distance is the maximum distance between two parallel plates where the flame is extinguished. This is equivalent to say that the quenching distance is the minimum distance between two parallel plates that allows for flame propagation. The analysis presented here was developed by (Turns, 2012). Fig. 1 presents the schematic of the model.

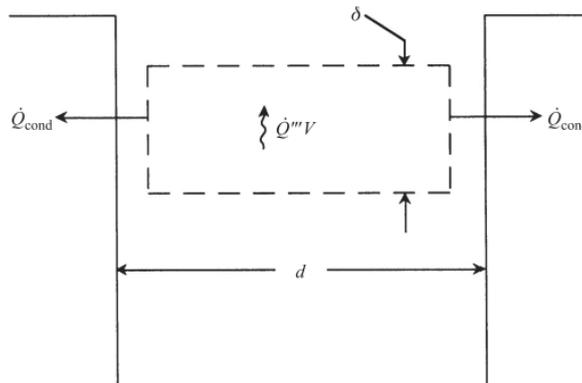


Figure 1. Schematic of flame quenching between two parallel plates (Turns, 2012).

The Energy conservation considers that heat is transferred from the flame to the walls by conduction. Fourier's law is used to determinate the heat conduction into wall, where  $k$  is conductivity,  $A$  is the area and the temperature gradient is evaluated in the gas at the wall. The adiabatic laminar flame thickness ( $\delta$ ), is defined as  $\delta = 2\alpha/S_L$ . Therefore, it depends on the laminar flame velocity ( $S_L$ ) and on the thermal diffusivity ( $\alpha$ ). The area is defined as  $A = 2 \delta L$ , where the factor 2 exist because the flame is in contact with the wall in two sides,  $L$  is the length of the slot. Eq. 1 relates the heat liberated on the combustion process to the heat transferred by conduction. The heat liberated by the combustion is expressed in terms of the fuel reaction rate ( $\dot{m}_f'''$ ), the difference on formation enthalpy between reactants and products ( $\Delta h_f$ ), and, the volume of the flame ( $V$ ). The difference in formation enthalpy can be expressed in terms of the sensible enthalpy gain as  $\Delta h_f = (v + 1)c_p(T_b - T_u)$ , which  $T_b$  is the burned gas temperature,  $T_u$  is unburned gas temperature,  $c_p$  is specific heat and  $v$  is stoichiometric air/fuel ratio.

$$\dot{Q}_f = \dot{Q}'''V = -\dot{m}_f''' \Delta h_f V \quad \text{Eq. 1}$$

The temperature gradient tends to the difference between the flame and wall temperatures divided by the quenching distance  $d$ ; However, a constant  $b$  is introduced to account for this oversimplification as shown in (Eq. 2). The factor  $b$  is greater than 2. This consideration implies that the gradient is linear in the region.

$$\frac{dT}{dx} = \frac{T_{flame} - T_{wall}}{d/b} \quad \text{Eq. 2}$$

The energy conservation is applied as shown in Eq.3. Then, the quenching distance is obtained as shown in Eq. 4. Therefore, the quenching distance is related to characteristic properties of flame, such as thermal diffusivity and laminar flame velocity (or adiabatic laminar flame thickness) and a parameter b. This parameter depends on the fuel and should be fitted with experimental data.

$$(-\dot{m}_f''' \Delta h_f)(\delta dL) = k(2\delta L) \frac{T_{flame} - T_{wall}}{d/b} \quad \text{Eq. 3}$$

$$d = \frac{2\sqrt{b}\alpha}{S_L} = \delta\sqrt{b} \quad \text{Eq. 4}$$

The phenomenon of flame quenching occurs when two mechanisms of flame propagation are affected, namely, thermal and mass diffusion. Tube walls remove heat from the flame, affecting the combustion phenomenon. The smaller the diameter of the tube, the greater is the surface to volume ratio and consequently the greater the heat loss is. Moreover, the smaller the tube is, it is easier to reduce the number of collisions of the active radical species. As it is known, the equivalence ratio affects the characteristic properties of the flame such as thermal diffusivity, temperature, and laminar flame speed. Equivalence ratio affects quenching distance in different manners, for example in Fig. 2a, for a fixed flame temperature, the quenching distance increases for non-stoichiometric mixtures. Notice that the higher the temperature, the smaller the quenching distance becomes. It may happen because heat losses are comparatively smaller than the heat release for high temperature and in consequence the chemical reactions are not readily deactivated (Glassman; Yetter; Glumac, 2015).

Initial pressure is another condition that affects premixed flame's characteristics. Quenching distance increases as pressure decreases,  $d \sim 1/P$ . The theory explains that the mean free path of molecules in gases increases as pressure decreases. Therefore, the number of collisions with the walls affects the species that are deactivate, high pressure means high number of collisions. In Fig 2b, the effect of pressure on quenching distance is presented. Tab. 1 shows the summary effects of pressure and temperature on quenching distance according to quenching theory.

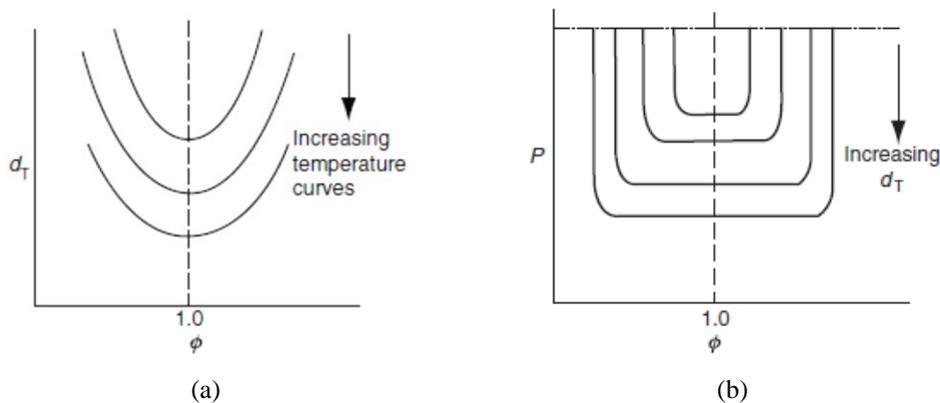


Figure 2 – (a) Variation of quenching distance ( $d_T$ ) as a function of equivalence ratio with initial temperature and (b) Effect of pressure on quenching distance. Available from (Glassman; Yetter; Glumac, 2015)

Table 1 – Effects of pressure and temperature on quenching distance.

Variable	Effect on quenching distance
pressure decrease	increase
pressure increase	decrease
temperature decrease	increase
temperature increase	decrease

## 2.2 Experimental Determination

An experimental study by Friedman and Johnston (1952) was performed measuring the quenching distance at different initial pressures and equivalence ratios for n-heptane (99.5%), iso-octane (99.6%), benzene (99%) and ethyl

ether. Experiments were conducted at an initial temperature of 100°C. The main conclusions are the existence of a relation between the quenching distance and the pressure given by  $d \sim p^{-n}$ . Fig. 3 presents the effect of pressure on quenching distance at 100°C. The smallest quenching distance occurred in mixtures with an equivalence ratio greater than one for each pressure and fuel. In addition, the quenching distance of the fuels tested in a stoichiometric mixture followed the following growth order: iso-octane > n-heptane > benzene ~ ethyl ether, while the flame speed followed the reverse order ethyl ether > benzene > n-heptane > iso-octane. Therefore, for mixtures with higher laminar flame speeds the quenching distances are lower.

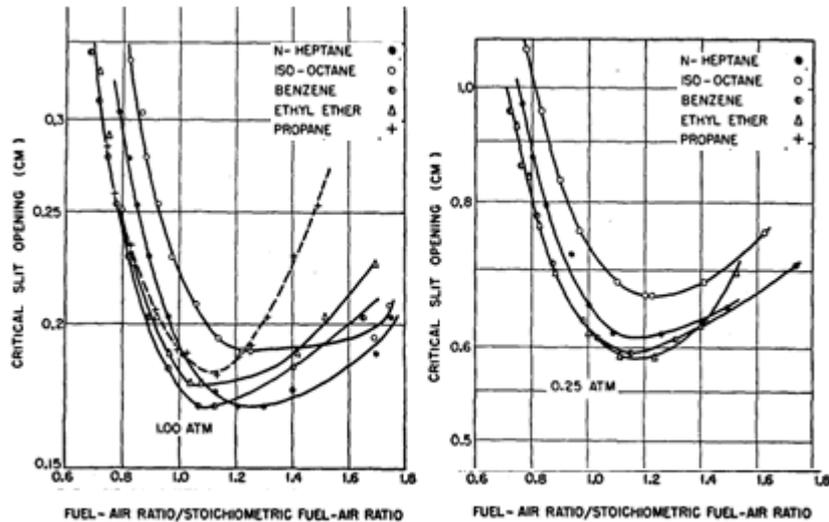


Figure 3 – Effect of pressure on quenching distance at 100°C. Fuels: n-heptane (99.5%), iso-octane (99.6%), benzene (99%) and ether ethyl. Adapted from: (Friedman; Johnston, 1952)

The influence of flame speed on the quenching distance was experimentally investigated by (Mahuthannan et al., 2019). Experiments using mixtures of methane-air, propane-air and ethylene-air were conducted in a rectangular section channel (similar to the Theoretical model presented in section 2.1.1) with initial temperature of the entire system of 293K and initial pressure close to atmospheric. Pressure sensors and fast Schlieren imaging were used to evaluate flame quenching. The results showed for both fuels that the quenching distance is smaller for laminar flames when compared to turbulent flames. In laminar flames, the quenching distance vary between 1.3 to 1.5mm, while for turbulent flames it becomes between 2 to 2.5mm. Fig.4 shows the quenching distance measured as function of flame speed at the entrance of rectangular channel. This observation is relevant in flame arrester design because operational conditions of a combustion system must be engineered to guarantee safety. If a deflagration occur accidentally in a pipeline, the flame arrester chosen should have a characteristic length near the quenching distance for the specific condition.

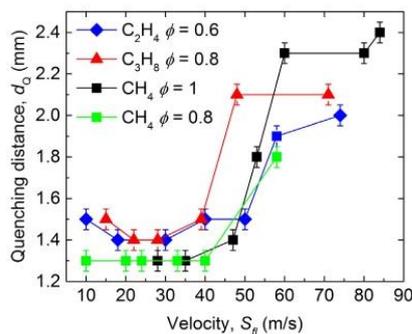


Figure 4 - Quenching distance as function of flame speed at the entrance of rectangular channel for different fuels. Available from: (Mahuthannan et al., 2019).

Combustion systems that operate in negative temperatures are the motivation to study quenching distance at low initial temperatures. Experiments with atmospheric pressure for cryogenic temperatures ( $T_w = 138K$  to  $293K$ ) using methane-air mixtures for flat plate and tube configurations were conducted by (Guiberti et al., 2020). For the temperature of 293K the results were compared with data from the literature, for both methods. The conclusion is that the quenching distance increases with decreasing of the initial wall temperature. For the flat plate case, the distance almost doubled from 0.17mm to 0.34mm for a decrease in temperature from 290K to 175K. For the case of tubes, it is possible to use larger

diameters for similar temperatures for instance  $d = 2.5\text{mm}$  for 293K and  $d = 3.5\text{mm}$  for 138K. In both experiments, the lower the initial temperature is, the higher the quenching distance becomes. Temperature influences the chemical kinetics. The flame reaction zone has high rate of radical release, which keeps the flame front in movement. The cryogenic wall temperature imposed in the experiments may reduce considerably the radical release, retarding the flame propagation. As result, the flame it is easier to quench a flame for cryogenic temperatures and it means that the quenching distance become bigger.

Recently a study performed combustion tests on a premixed hydrogen-air flame to assess its behavior when crossing perforated-plates. The flame evolution, speed characteristics and pressure dynamics were studied (Wan et al., 2020). These plates have orifices of 1mm diameter and different lengths ranging from 20mm, 40mm, 60mm, 80mm and 100mm. High-speed Schlieren photography was used to monitor the evolution of the flame behavior and measure the flame front speed. Two pyroelectric pressure sensors were used to measure the pressure locally, the first was installed upstream of the perforated plate and the second downstream. The results indicated the existence of three flame phenomena on the plate, "passes", "quench" and "near limit". The "pass" case is characterized by the complete propagation of the flame through the orifice, involving laminar, jet and turbulent flames. Three pressure peaks were identified downstream, the first peak being equal to twice the initial pressure, the second pressure peak is caused by overpressure and the third is caused by a reflection of the pressure wave in the system. The flame speed in the upstream region decreases with the length of the plate orifices. The "quench" case is characterized by a laminar flame that is not able to cross the plate. The "near limit" case is related to the length of the orifice in the plate because no obvious flame and induced turbulence were observed in the upstream region. The heat transfer from the flame to the walls is greater for the longest orifice plates, and consequently the critical pressure and the quenching limit are greater.

Experiments conducted by the authors above show how quenching distance depends on the experiment setup. Mixture compound, initial pressure and wall temperature influence on quenching distance. The process of heat loss in increased when temperature wall is decreased, which means that quenching distance increases. This characteristic is relevant when dimensioning flame arrester, because a bigger diameter in a flame arrester reduces the pressure loss. Flame speed is capable to influence quenching distance especially when turbulence effects are present, see Fig. 4.

The theoretical approach presented in section 2.2.1 by the Eq. 4, was employed to determinate the value of parameter  $b$ . Experimental data of quenching distance and flame speed (Fig.4) presented by Mahuthannan et al. (2019) were explored in this case. The thermal diffusivity was assumed as air and avaliated at a film temperature, between the 298K and the adiabatic flame temperature which was determined using CEA NASA RUN for Assigned Enthalpy and Pressure accordind to fuel and equivalence ratio. The Fig. 5 presents the parameter  $b$  of Eq. (4) estimated according to the different flame speeds given in Fig. 4. The fuels are methane, ethane and propane. It is observed that the value of  $b$  increases with increasing flame speed. The equivalence ratio can influence the parameter  $b$  value because the flame speed also depends on ER. Considering approximately equal flame speeds it is observed that the parameter  $b$  is greater for stoichiometric methane – air than for lean methane – air mixtures.

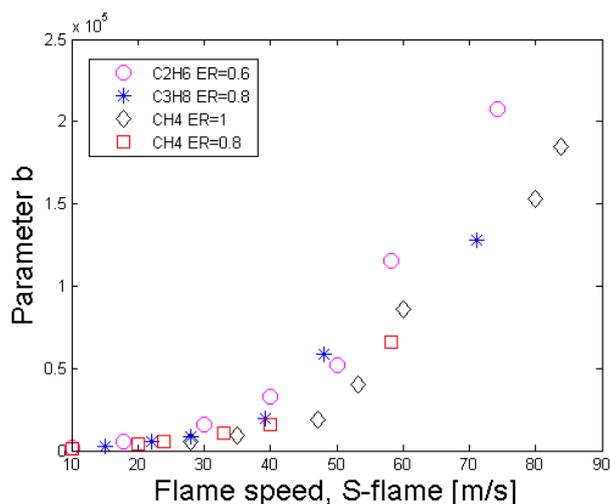


Figure 5 – Parameter  $b$  estimated for methane, ethane and propane.

### 2.3 Numerical Modelling

Combustion is modelled as a reactive multi-component fluid with N species. The overall mass conservation and the species conservation equations are presented in Eqs. 5 and 6. The momentum conservation equation is presented in Eq. 7 and the energy conservation equation is shown in Eq. 8. (Thierry Poinsot, 2005).

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \quad \text{Eq. 5}$$

$$\frac{\partial \rho Y_k}{\partial t} + \vec{\nabla} \cdot (\rho (\vec{u} + \vec{V}_k) Y_k) = \dot{\omega}_k \quad \text{Eq. 6}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \otimes \vec{u} + P I) = \vec{\nabla} \cdot \underline{\tau} + \rho \vec{g} \quad \text{Eq. 7}$$

$$\frac{\partial \rho e_{tot}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} h_{tot}) = \vec{\nabla} \cdot (\underline{\tau} \cdot \vec{u} - \vec{q}) + \rho \vec{g} \cdot \vec{u} - \dot{\omega}_q \quad \text{Eq. 8}$$

Numerical modelling has been applied to predict the quenching distance of hydrogen, especially because this fuel offers high risk of explosions close to essential equipment in industry. Laminar hydrogen flame in presence of quenching mesh in two-dimensional unsteady was studied. A global reaction mechanism was employed  $2H_2 + O_2 \rightarrow 2H_2O$ . The governing equations are the Navier-Stokes equations, mass conservation for species, energy conservation. The sketch simulated is presented in Fig. 6 using the characteristic diameter  $D=0.3\text{mm}$  (Kudriakov; Studer; Bin, 2011). Mesh size affected the results, the coarse mesh (1134 elements,  $dx=0.02\text{mm}$ ) quenched the flame while fine mesh (10354 elements,  $dx=0.0092\text{mm}$ ) did not affect. The conclusion of this study insights the mechanism of flame quenching, the process of heat loss close to wall quenched the flame when crossing the obstacle while in the up section the flame propagated. The author suggested investigating the same problem employing a detailed mechanism.

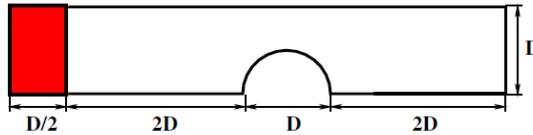


Figure 6 – Sketch of discretized domain. Available from: (Kudriakov; Studer; Bin, 2011)

In another study, a numerical analysis of laminar premixed hydrogen-air flames was developed using global and detailed chemical kinetics mechanisms. A two-dimensional and unsteady analysis was carried out to predict the flame front interaction with a 0,3 mm quenching mesh. The governing equations and the sketch domain is the same as presented by (Kudriakov; Studer; Bin, 2011). The main conclusion was that the global mechanism did not predict flame quenching while the detailed mechanism predicted flame quenching by the mesh (Pfeiffelmann; Benim, 2018). Fig. 7 shows the numerical simulation of temperature distribution for  $125\mu\text{s}$  after ignition, (a) represents global mechanism and (b) represents detailed mechanism. There is a huge difference between the two mechanisms, the detailed mechanism considered 19 reactions while the global mechanism represents a one-step reaction. The transport properties and the thermodynamic properties are calculated locally. By this way, the detailed mechanism is able to represent better the physical phenomenon.

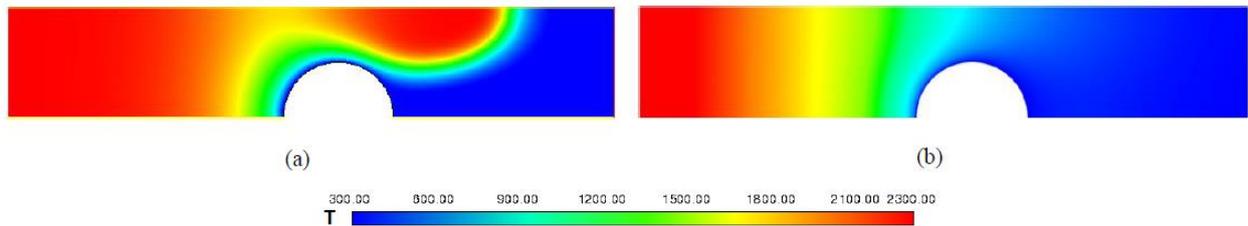


Figure 7 - Predicted temperature fields  $125\mu\text{s}$  after ignition (a) global mechanism (b) detailed mechanism. Adapted from: (Pfeiffelmann; Benim, 2018)

Gutkowski (2011) investigated the influence of the number of steps on the reaction mechanism (SRM) under quenching conditions for propane-air mixtures. One and two step reactions were compared numerically for circular tubes using CFD. The two steps mechanism presented better results for quenching distance when compared to experimental data, especially for leaner mixtures. This result reinforces the information presented in Fig. 6, which means that detailed mechanisms are better for modelling quenching distance phenomena.

The articles presented in this paper indicate that quenching distance can be obtained using numerical simulations. The conditions employed during the modelling of the problem are very important to define and even obtain accurate predictions, an example is the result presented in Fig. 6. Detailed mechanism reactions are necessary to describe the problem properly, intermediate species are able to change temperature fields and even produce diffusional processes inside the flame. The number of intermediate species vary accordingly to the mechanism and fuel complexity. Because of that, the mixture properties might vary. The assumptions taken are also relevant, for example neglecting radiation heat transfer and buoyancy forces in the energy and momentum conservation equations, respectively; makes it not possible to determine the quenching distance without ambiguities. It is important to notice that these approximations are normally assumed to reduce computational time.

## 2.4 Empirical Models and correlations

Quenching distance between two parallel plates were studied by Friedman and Johnston (1950) using mixtures of propane-air. The influence of temperature was studied at constant atmospheric pressure. Two cases were considered, (a) the initial quenching plate temperature varied from 300K to 652K and (b) the initial gas mixture temperature varied from 300K to 558K. The author concluded that the quenching effect is diminished with plate temperature increment. As a result of varying the initial mixture temperature an empirical correlation was proposed, which is shown in Eq. 9, where the temperature is in Kelvin (K) and  $dq$  is quenching distance in inches. For stoichiometric and rich mixtures, the n-factor is equal to 0.5 and for lean mixtures the n-factor increases to 0.85. The n-factor increasement for lean mixtures is expected because lean mixtures provide higher values for quenching distance. Fig. 8 shows the evolution of quenching distance using Eq. 9 for a range of initial temperatures from 300K to 500K. For temperature of 300K the lean mixture can be compared to results available in Fig. 4, which presents a propane – air mixture with equivalence ratio of 0.8. In the range of 10-40 cm/s the experimental data is in agreement with the results predict by the correlation.

$$dq = T^{-n} \quad \text{Eq. 9}$$

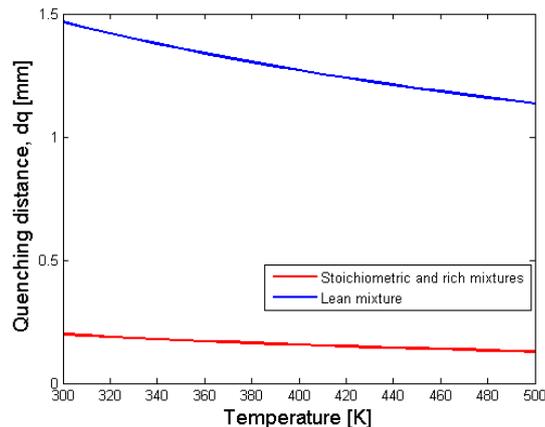


Figure 8 - Predicted quenching distance for propane at lean, stoichiometric and rich mixtures according to initial temperature at atmospheric pressure.

Experiments conducted by Friedman and Johnston (1952) also proposed an empirical model. Using the Eq. 10, the n-factor was fitted in accordance with results presented in Fig. 3. The n-factor for fuels tested are presented in Tab. 2. The empirical model is valid in the pressure range from 0.083 to 2,77 atmospheres.

$$d = p^{-n} \quad \text{Eq. 10}$$

Table 2 – n-factor fitted for Eq. 10. Adapted from: (Friedman; Johnston, 1950) and (Friedman; Johnston, 1952).

Fuel	n - factor
n-heptane	0.92
iso-octane	0.91
benzene	0.91
ethyl ethene	0.87
propane	0.91

Mixtures of methane and hydrogen with air were investigated to determine the quenching distance in parallel plates (Fukuda; Korematsu; Sakamoto, 1981). An empirical correlation (Eq. 11) was developed to predict quenching distance

according to pressure in mmHg. Tab. 3 presents the coefficients fitted according to the percentage of H<sub>2</sub> in the fuel mixtures at stoichiometric conditions by using the least squares method. The main conclusion is that quenching distance increases when initial pressure decreases and the addition of small percentage of hydrogen in the fuel mixture increases the quenching distance.

$$d = C \left( \frac{P}{760} \right)^{-B} \quad \text{Eq. 11}$$

Table 3 – Values of *C* and *B* for Eq. 10. Adapted from: (Fukuda; Korematsu; Sakamoto, 1981)

% H	<i>C</i>	<i>B</i>
0	2.16	0.93
25	1.84	0.74
50	1.47	0.81
75	0.98	0.81
100	0.55	1.09

An empirical model was proposed through visualization in the experiments carried out by Takizawa et al. (2015) in an apparatus with parallel plates similar to ASTM E582. Quenching distance was analyzed with highly to mildly flammable compounds, see Fig. 9. There were 11 fuels tested with air. Most of these flammable compounds elucidate characteristics of low-GPW (global warming potential). The relations were built relating quenching distance to  $\rho_0$ , maximum laminar flame speed,  $S_{u0,max}$ , and fitted constants. The maximum error was 11.9%, while the average error was 4.2%. Eq. 12 indicates de correlation.

$$d_{q,h} = 58.12(\rho_0 S_{u0,max})^{-0,926} \quad \text{Eq. 12}$$

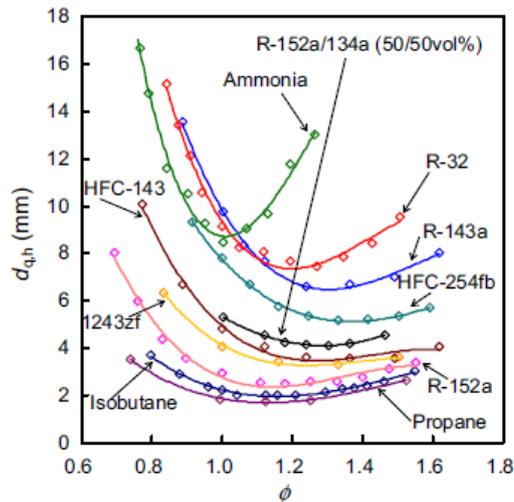


Figure 9 – Quenching distance measured as function of equivalence ratio. Available from: (Takizawa et al., 2015)

The correlations available to determinate quenching distance are in accordance to theory presented on section 2.2.1. The curves presented in Fig. 8 are similar in some degree to theory curve in Fig. 2 (a). Stoichiometric mixtures and rich mixtures (ER close to 1.1) presented the minimum quenching distance. Lean mixtures and richer mixtures showed higher values for quenching distance, being also in accordance with experimental data in Fig. 3.

### 3. CONCLUSIONS

In the present work, a review of quenching distance was developed to enhance the understanding of the phenomenon. Quenching distance is an essential characteristic of flame employed to develop flame arresters, which depends on the fuel, equivalence ratio, and initial temperature and pressure.

The theoretical model uses simplified considerations to determine the quenching distance through energy conservation considerations. Experimental results agreed with the quenching theory, stoichiometric mixtures and rich mixtures (ER~1.1) presented the lowest value for quenching distance while lean mixtures presented higher values for quenching distance. The dimensionless parameter  $b$  for quenching distance model was calculated using experimental data. This parameter was plotted according to flame speed and it seems to have a dependence because the increment of speed made the parameter assume higher values independent of the fuel.

For numerical modelling, detailed mechanisms and refined meshes showed better results when compared to experimental data. Detailed mechanisms are able to represent better the physical phenomenon due to the quantity of species involved. For hydrogen, the detailed mechanism predicted the flame quenching.

Experimental data fitted well with correlations that involved powers of the temperature, pressure and flame speed for different fuels. Quenching distance predicted by correlation also agreed with experimental data for equivalence ratio variation.

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### 5. RESPONSIBILITY NOTICE

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