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SIGNIFICANCE TEST IN EXPERIMENTAL DETERMINATION OF THE QUENCHING DISTANCE FOR *n*-BUTANE-AIR MIXTURES AT VARIOUS INITIAL PRESSURES

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abstract: An empirical correlation between quenching distance, qd, and initial pressure, p_0, has been used to estimate the model parameters for the butane-air mixture through linear regression. The tests of significance of the two models for $qd = qd(p_0)$ dependence for several data sets obtained at different insulating disk diameters and close to stoichiometric compositions of butane in air have been made. The results were further analysed in view to evaluating the performance of the experimental technique.

key words: significance test; quenching distance; *n*-butane-air mixture

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Introduction

An important critical characteristic of the process of flame quenching is represented by the quenching distance. It has a wide use among design and safety engineers or combustion scientists to develop either adequate prevention/protection in case of accidental explosions, or more efficient and environmental friendly engines. As the experimental methods used to acquire quenching distances is concerned, several different techniques are applied, but the most used is the standardized flanged electrode technique [1].

The reported experimental quenching distances are, however, widely spread because it usually contain "the history" of their obtainment [2,3], with dependency on either the particular conditions of the experiment or the human operator's condition, or even the limitations of the technique, that both contribute with additional quantities to the associated experimental uncertainty. The present study is therefore focused on the capability of this experimental technique to provide pressure profiles of the quenching distance within an acceptable range of variation.

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Experimental

The explosion test cell [4] has been adjusted to accommodate insulating disk flanges of 10 mm, 20 mm, and 40 mm diameter, respectively. *n*-Butane and air (5.0 grade, SIAD RG, Italy) have been used to formulate compositions varying from 2.60% to 6.00%, by partial pressure method. Usual absolute pressure of the mixture was 500 kPa, and operating maximum pressure 150 kPa. The cylinders (10 L capacity) containing fresh prepared *n*-butane/air mixture have been hold still at least 24 hours before use, to allow homogenization of the gaseous mixture.

The experimental quenching distance has been measured with respect of the initial pressure, which ranged from 21.3 to 101.3 kPa, for the two disk diameters taken into consideration.

Results and Discussion

The best-fit empirical equation that properly describes the dependence of the quenching distance *versus* initial pressure is [5,6]:

$$y = a + \frac{b}{x} \tag{1}$$

where the initial pressure is the independent, x, and the quenching distance is the dependent, y, variable. The model equation (1) was tested on experimental sets obtained at fixed initial pressure for five different mixtures C_4H_{10}/air: 2.60, 3.13, 4.00, 5.00 and 6.00%, each experiment being recorded at two flange diameters 10 and 40 mm respectively; a second set of data was obtained with the quenching distance as the independent variable and the initial pressure as the dependent one. The equation fitted on the experimental data was obtained from equation (1) changing the variables:

$$y = \frac{b}{x - a} \tag{2}$$

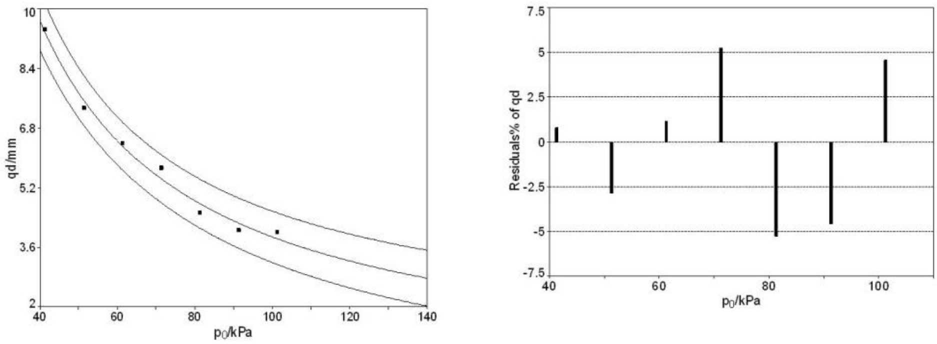
The goodness of fit was checked on all experimental sets for both methods. The prediction band for a confidence level of 95% was plotted to show the scatter of data, since this band accounts for uncertainty in the curve itself. The residuals graphs also show that the residual of each point of the curve $y_{\mathrm{exp}} - y_{\mathrm{predicted}} \big/ y_{\mathrm{exp}}$ is less than 10%, the accepted limit in the experimental errors. The next problem to deal was if these residuals are randomly distributed. In order to determine whether the curve deviates systematically from the experimental data, the runs test [7] was accomplished. A run is a series of consecutive points that are either all above or all bellow the regression curve. Let N_+ to be the number of points above the curve, N_- the number of points below the curve and $N = N_+ + N_-$. The observed number of runs is:

$$n_{\mathrm{r\ obs}} = \frac{2 \cdot N_+ N_-}{N_+ + N_-} + 1 \tag{3}$$

In most cases the numbers of points above and below are equals so, with this approximation the expected number of runs has to be:

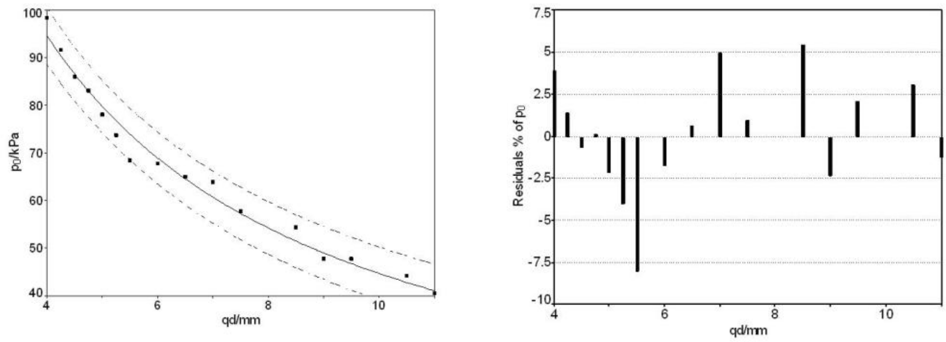
$$n_{\mathrm{r\ expected}} = 1 + \frac{N}{2} \tag{4}$$

The observed number of runs being nearly equal to the expected one for all the 20 experiments proved that the chosen regression model is appropriate. For example, in Figs. 1 and 2, the prediction bands and the residual plots are shown for the 2.60% C_4H_{10} mixture, when a 10 mm flange diameter was used.



(a) *(b)*

Fig. 1 (a) 95% *Prediction band and* (b) *residual plot of quenching distance versus initial pressure profile*
Conditions: 10 mm flange diameter, 2.60% C_4H_{10} /air



(a) *(b)*

Fig. 2 (a) 95% *Prediction band and* (b) *residual plot of initial pressure profile versus quenching distance profile*
Conditions: 10 mm flange diameter, 2.60% C_4H_{10} /air

The main estimated parameters are given in Tables 1 and 2.

The comparison of the two methods has been done with the paired *t*-test [8] using the following null and two-tailed alternative hypotheses:

$$\boldsymbol{H_0}:\ \overline{\mathrm{diff}} = 0 \qquad \boldsymbol{H_A}:\ \overline{\mathrm{diff}} \neq 0 \tag{5}$$

Table 1 Estimated parameters of several butane/air mixtures for 10 mm flange diameter.

% C_4H_{10}	Parameter	Best-fit		*SD*	
		Method 1	Method 2	Method 1	Method 2
2.60	*a*	–0.0023	–1.37	0.2984	0.29
	b	388	508	18	22
	r^2	0.9886	0.9817		
3.13	*a*	0.0302	–0.583	0.5413	0.051
	b	339	223	29	4
	r^2	0.9585	0.9980		
4.00	*a*	0.28	–0.427	0.12	0.063
	b	157.8	194.9	4.9	4.6
	r^2	0.9954	0.9943		
5.00	*a*	0.467	0.32	0.043	0.12
	b	132.5	121.7	1.8	8.8
	r^2	0.9986	0.9735		
6.00	*a*	1.15	0.19	0.12	0.11
	b	116.5	177.0	5.4	8.3
	r^2	0.9853	0.9857		

Table 2 Estimated parameters of several butane/air mixtures for 40 mm flange diameter.

% C_4H_{10}	Parameter	Best-fit		*SD*	
		Method 1	Method 2	Method 1	Method 2
	a	1.34	–0.054	0.63	0.17
2.60	*b*	463	331	39	13
	r^2	0.9656	0.9879		
	a	-0.602	–1.049	0.081	0.081
3.13	*b*	201.5	218.7	4.3	6.4
	r^2	0.9973	0.9937		
	a	0.110	–0.854	0.059	0.083
4.00	*b*	145.3	153.5	2.5	6.2
	r^2	0.9979	0.9871		
	a	0.527	–0.541	0.041	0.066
5.00	*b*	143.3	159.6	2.2	4.9
	r^2	0.9986	0.9936		
	a	1.61	1.09	0.094	0.12
6.00	*b*	184	174.4	5.00	9.8
	r^2	0.9955	0.9863		

Defining the difference between the methods as:

$$\text{diff} = b_{\text{method}\,2} - b_{\text{method}\,1} \text{ for parameter } b \text{ and}$$

$$\text{diff} = a_{\text{method}\,2} - a_{\text{method}\,1} \text{ for parameter } a$$

The difference for each experiment together with the mean and standard deviation are summarized in Table 3. The test statistic $t_{\exp}$ is derived from a confidence interval around $\overline{\text{diff}}$:

$$0 = \overline{\text{diff}} \pm \frac{t_{\exp} \cdot SD}{\sqrt{n}} \tag{6}$$

where n = 5 is the number of paired experiments and SD is the standard deviation. Rearranging the equation one obtains $t_{\exp}$:

$$t_{\exp} = \frac{\left|\overline{\text{diff}}\right| \cdot \sqrt{n}}{SD} \tag{7}$$

The results are given in Table 3.

Table 3 Paired *t*-test for methods 1 and 2.

% C_4H_{10}	10 mm flange parameter		40 mm flange parameter	
	Diff$_i$ for *a*	Diff$_i$ for *b*	Diff$_i$ for *a*	Diff$_i$ for *b*
2.60	–0.00025	–11	–1.34	–134
3.13	–0.02962	116	0.00009	17.2
4.00	–0.27997	–4.7	–0.11	–13.3
5.00	–0.142	10.8	–0.53	–29.3
6.00	–0.960	–62.5	–0.523	–9.6
$\overline{\text{diff}}$	–0.282	9.72	–0.499	–33.8
SD	0.394	65.5	0.526	58.45
$t_{\exp}$	1.60	0.33	2.12	1.29

The value of $t_{\exp}$ was compared with the critical value t_{crit} (0.05, 4) = 2.78 where α = 0.05 is the chosen significance level and n–1 = 4 the degrees of freedom for paired data. Since $t_{\exp}$ for both parameter is less than t_{crit} (0.05, 4) for both flange diameters, the null hypothesis is retained and there is no evidence that the two methods yield different results at the stated significance level. The paired *t-test* was also performed in order to check a possible significant difference between the parameters' values obtained for 10 and 40 mm flange diameters. The results are further tabulated (Table 4).

In both cases $t_{\exp}$ was less than the critical value value t_{crit} (0.05, 4) = 2.78 for *a* as well as for *b*, using both experimental methods. However, a problem arises from the large experimental errors affecting parameter *a*: the standard deviations for *a* exceed the best-fit value with more than an order of magnitude, this parameter being more sensitive to the experimental errors than *b*.

Table 4 Paired test for the two flange diameters using method 1 and 2.

% C_4H_{10}	Method 1		Method 2	
	Diff$_i$ for *a*	Diff$_i$ for *b*	Diff$_i$ for *a*	Diff$_i$ for *b*
2.60	1.34	76	$-1.1\cdot10^{-6}$	–69
3.13	–0.031	–164	$-4.9\cdot10^{-4}$	–35
4.00	–0.17	–12.4	$-3.0\cdot10^{-5}$	–46.5
5.00	0.060	10.8	–0.325	11.7
6.00	–0.063	57.9	0.900	–4.75
$\overline{\text{diff}}$	0.331	4.34	0.115	–28.71
SD	0.612	97	0.461	32.35
t_{exp}	1.21	0.10	0.56	1.98

Even if the paired *t*-test applied to the best-fit values of *a* calculated for both flange diameters and both experimental methods clearly proved that there is no significant difference between the best-fit values, a consistent conclusion can be achieved only after comparing the standard deviations of *a* with the same statistic test.

The experimental values of the *t* parameter when comparing the experimental methods were: t_{exp} = 0.61 for 10 mm flange diameter and t_{exp} = 0.18 for 40 mm flange diameter, respectively; when comparing the values of the standard deviation of *a* for 10 and 40 mm flange diameters, one obtains t_{exp} = 0.08 with method 1, and t_{exp} = 1.98 with method 2. Consequently, the null hypothesis should be retained and the alternative hypothesis should be rejected. Ones can finally state that there is no evidence for significant model or systematic errors to affect the experimental data, as proved by the random distribution of residuals as well as through the runs tests.

Conclusions

The results of the statistic analysis presented herein prove that the flanged electrode method used to directly measure the quenching distance of *n*-butane-air flame cannot be questioned about significant random or systematic errors. This is important especially knowing that the quenching distance can be easily correlated with other critical flammability parameters such as minimum ignition energy or maximum experimental safe gap that, in turn, cannot be obtained as easily as the quenching distance is.

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