Experimental Measurements of Turbulent Burning Velocity in Gas Explosions with Two Obstacles of Variable Spacing: Implication to Gas Explosion Scaling

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1 Introduction

Most gas explosion tests from inception were conducted in small scales. The relatively low costs and environmental impact of the reduced-scale experiments made them an attractive choice. It was shown by [1] that flame speeds, S_f and overpressures, P generated in undersized-scale experimentations were lower than those produced on a large scale tests. This was as a result of the presence of hydrodynamical instabilities which influenced the initial flame speed propagation on large scale and also due to the effect of turbulent length scale on the burning rate. In order to replicate large-scale overpressure at small scale, it is required to reproduce the S_f speeds at the same relative position in the rig since $P \propto S_f^2$ in vapour cloud explosions. As a consequence, two scaling techniques are used to relate small-scale test results with those that would be expected from the actual geometry [2-3]. The accuracy of these scaling techniques depends on the turbulent combustion models which were derived from small-scale experiments.

Until now, there exist several experimental and theoretical methods in the literature on turbulent burning velocity, S_T models by a number of researchers. Among all the parameters that influence S_T, the integral length scale, ℓ is the main determining factor in gas explosion scaling [4]. Therefore scale of importance in turbulent combustion is not the whole size of the rig but rather the size of the turbulent generator as this determines the ℓ. In explosions the turbulence initiators are the obstacles and for grid plate obstacle or similar the dimension that defines ℓ is the width of the solid materials between the holes [5]. For a significant interpretation of results by most researchers from small scale tests and for application to actual size explosion hazards, the understanding of the influence of ℓ is necessary.

It is the aim of this paper to experimentally measure the S_T in gas explosions with two obstacles of variable spacing with a view to looking at its implication to gas explosion scaling.

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2 Experimental

An elongated cylindrical vessel 162 mm internal diameter with a length-to-diameter, L/D of 27.7 was used to perform the tests with its open end connected to a large cylindrical dump-vessel with a volume of 50 m^3 as shown in Fig 1. This arrangement enabled the simulation of open-to-atmosphere explosions with accurate control of both test and dump vessels pre-ignition conditions.

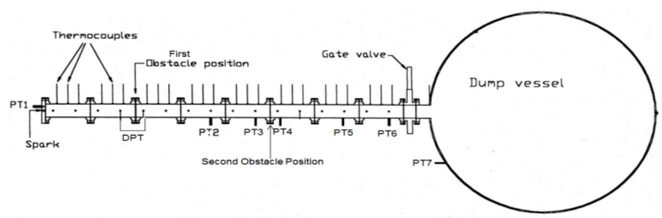

Fig 1. Schematic diagram of the experimental set up.

A pneumatically actuated gate valve was used to isolate the text vessel from dump vessel. Two obstacle configurations (orifice plate) made from 3.2 mm thick stainless steel of 20 – 40 blockage ratio each were used as obstacles to generate turbulence in the test vessel. The first obstacle was positioned 1 m downstream of the spark (for all tests) while the second obstacle's position was varied from 0.5 m to 2.75 m downstream of the first obstacle. A 10% methane-air by volume formed by partial pressure was used as the flammable mixture. After mixture circulation, allowing for at least 4 volume changes, the gate valve to the dump vessel was opened and a 16 Joule spark plug ignition was effected at the centre of the test vessel closed-end flange. An array of 24 type-K thermocouples and 7 Keller-type pressure transducers, PT (PT1 -PT7) were used to measure the flame speed and explosion overpressure respectively. However, differential pressure transducer, DPT and PT3/PT4 were used to measure pressure drop, ΔP_s across the first and second obstacles respectively. From the obtained $\Delta P_{s,}$ turbulent combustion parameters such as unburned gas velocity, S_g, root mean square velocity, u', Reynolds number, R_ℓ Karlovitz number and S_T were measured.

Table 1. Summary of experimental tests conditions and results

Test	BR (-)	x_s (m)	b (m)	L (m)	S_g (m/s)	P_{max} (bar)	S_{fmax}(m/s)	u'/S_L (-)	R_ℓ(-)	S_T(m/s)	Ka(-)
1	0	-	-	-	-	0.256	122	-	-	-	-
2	0.2	-	0.024	0.012	44	0.566	198	15	5606	26	0.46
3	0.2	1.75	0.024	0.012	98	0.995	290	25	11115	39	0.94
4	0.2	2.25	0.024	0.012	124	1.164	362	20	8866	48	0.68
5	0.2	2.75	0.024	0.012	79	0.710	240	32	12827	32	1.39
6	0.3	-	0.033	0.017	41	1.091	270	18	9390	36	0.52
7	0.3	0.5	0.033	0.017	80	1.623	307	35	18416	41	1.40
8	0.3	1.0	0.033	0.017	114	1.850	381	50	35981	51	2.03
9	0.3	1.25	0.033	0.017	132	2.198	465	58	41236	62	2.56
10	0.3	1.75	0.033	0.017	153	2.680	486	67	45793	65	3.26
11	0.3	2.25	0.033	0.017	116	1.858	381	50	32078	51	2.23
12	0.3	2.75	0.033	0.017	64	1.222	323	28	19330	40	0.88

13	0.4	-	0.043	0.022	34	1.649	370	23	14952	49	0.66
14	0.4	1.25	0.043	0.022	138	3.103	573	93	85532	77	4.63
15	0.4	1.5	0.043	0.022	160	3.378	716	107	90888	96	5.97
16	0.4	2.25	0.043	0.022	128	2.085	522	86	77637	70	4.14

BR = obstacle blockage ratio, x_s = obstacle separation distance, b = obstacle length scale, S_L = laminar burning velocity

3 Derivation of New S_T Model with Dependence on Scale, ℓ

In order to obtain an S_T model with dependence on ℓ, the R_ℓ given as the ratio of $u'\ell$ and kinematic visocosity, ν has to be incorporated. Figure 2 shows a plot of dimensionless turbulent burning velocity, S_T/S_L against the R_ℓ. The equation of the fitted curve had the form of,

$$\frac{S_T}{S_L} = 2.99 R_\ell^{0.36} \qquad (1)$$

The empirical correlations shown above have demonstrated a dependence on the length scale. The dependence on ℓ, is significantly higher than most of the S_T models but it is closer to that of Phylaktou and Andrews [6].

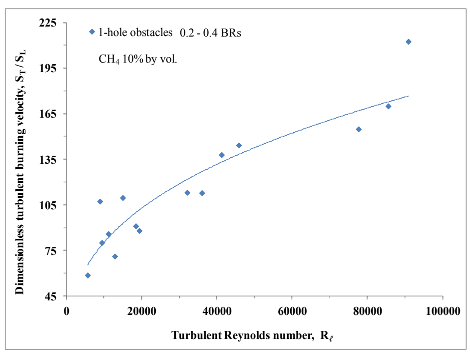

Fig. 3 Relationship between S_T/S_L and turbulent Reynolds number.

4 Derivation and Validation of Scaling Relationships for Overpressures

Phylaktou and Andrews [6] formulated a pioneer equation (see Eq. 2) in the explosion protection literature that gave an explicit dependence of the explosion overpressure on the geometric configuration, pressure loss characteristics (effectively the blockage ratio of the obstacles, BR) and mixture properties. The correlation was derived from their S_T correlation and validated against the limited suitable experimental data and showed a good agreement.

$$P \propto \left[\left(C_T\sqrt{K}\right)^{1.56}\ell^{0.62}\right]\left[E^{3.56}S_L^{2.62}L_e^{-0.92}(v/v_a)^{1.28}\right] \text{ Phylaktou's model [6]} \qquad (2)$$

where C_T is turbulence generation constant; K is pressure loss coefficient; E is the gas expansion ratio, L_e is the Lewis number and v/v_a is the kinematic viscosity ratios. The S_T obtained in the present research (Eq. 1) and those currently in use to model gas explosions using [7-10] were used to derive the scaling relationships for overpressure based on the approach of Phylaktou and Andrews [6]. The respective explosion overpressure, P equations are given in Eqs. 3-7 as,

$$P \propto \left[\left(C_T\sqrt{K}\right)^{0.54}\ell^{0.54}\right]\left[E^{2.54}S_L^{2.54}v^{-0.54}\right] \quad \text{Present model} \qquad (3)$$

$$P \propto \left[\left(C_T\sqrt{K}\right)^{0.52}\ell^{0.52}\right]\left[E^{2.52}S_L^{2.52}\nu^{-0.52}\right] \quad \text{Gouldin's model[7]} \qquad (4)$$

$$P \propto \left[\left(C_T\sqrt{K}\right)^{0.82}\ell^{0.39}\right]\left[E^{2.82}S_L^{2.39}\nu^{-0.39}\right] \quad \text{Bray's model[8]} \qquad (5)$$

$$P \propto \left[\left(C_T\sqrt{K}\right)^{1.1}\ell^{0.3}\right]\left[E^{3.1}S_L^{2.3}L_e^{-0.6}\nu^{-0.3}\right] \quad \text{Bradley's model [9]} \qquad (6)$$

$$P \propto \left[\left(C_T\sqrt{K}\right)^{1.5}\ell^{0.5}\right]\left[E^{3.5}S_L^{2.5}\nu^{-0.5}\right] \quad \text{Zimonts's model [10]} \qquad (7)$$

The relevant experimental work performed both at laboratory and large scales by Bjorkhaug [11] were used to validate the newly derived overpressure equations. A radial vessel with 17^o (pie) sector of a full cylindrical disk with solid walls at top, bottom, sides, and open to outer radius was used in these experiments. Ignition was effected at the apex of the vessel which is the centre of the imaginary full disk. Five obstacles of variable blockage ratios were used to generate turbulence in the experiments. The evenly spaced obstacles along the length of the vessel were either thin metal strips or round tubes. The influence of sharp/thin and thick/round obstacles on intensity of turbulence and hence overpressure was discussed in [12]. In the present validation, the results from the sharp/thin obstacles were considered. Stoichiometric methane and propane air mixtures were used to perform the explosions in both small and large scale geometries.

In the small scale (laboratory) tests, a vessel of 0.5 m long was used. The pitch and the height of the obstacles were kept at 0.1 m and 0.016 m respectively. However, the height of the vessel was adjustable and this permitted the study of the blockage ratios to be altered from 0.3 to 0.75.

Figure 4 show the experimental overpressures as a function of obstacle blockage for methane (4a) and propane (4b). Also shown in those figures are the respective predicted overpressures based on the newly derived models (Eqs. 3 -7). The constant of proportionality in each equation was obtained from fitting that equation to the methane test with the 0.54 blockage ratio obstacle labelled as "reference point" in Fig. 4a only. However, it should be noted that the constant is not universal but only applicable to this geometry. With the constant calculated in each equation, the equations became absolute (for this specific geometry) and were used to determine the overpressures at the various obstacle blockages for both gas/air mixtures. The turbulence generation constant, C_T was taken as 0.225 (for sharp/thin obstacles) whereas the pressure loss coefficient, K was calculated from the correlation of Ward Smith [13]. The integral length scale, ℓ was taken as half the obstacle height and the mixture properties from [6] were used. The predicted overpressures shown as data points were in good agreement with the experimental overpressures shown as dashed lines for both fuels and range of obstacle blockage used.

The author also reported the overpressure results from a large-scale rig akin to the small scale geometry described above [11]. The large scale vessel had the identical disc-sector shape, 10 m long and the spacing between obstacles was 2 m. This corresponded to a scale increase by a factor of 20. For tests with methane-air mixtures, three obstacle blockage ratios, BRs of 0.16, 0.3 and 0.5 were used while propane-air mixtures had only 0.16 and 0.5 BRs.

Figure 5 presented the experimental measured overpressures in the large scale tests for methane (5a) and propane (5b) air mixtures respectively. Also shown are the predicted overpressures from Eqs. 3-7 with similar proportionality constant as obtained from the single methane-air test with 0.54 obstacle blockage at the small-scale experiments and assuming complete geometric comparison between the laboratory (small) and large-scale tests with a scale ratio of 20. For both methane and propane-air mixtures, the calculated overpressures were in a close agreement with the experimental data especially for models with high integral length scale, ℓ exponent.

This agreement is very promising as it reveals that from using geometry at laboratory scale in the present research to calibrate the present equation (Eq. 3), then the effects of different blockage ratios, gases and scales for the same overall geometry could be successfully predicted.

None of the current gas explosion scaling techniques [2-3] has been utilized for such an extensive predictive application based on data from a single test performed at laboratory scale. However, by incorporating certain parameters dependence on overpressures, the predictive ability of the models used in scaling techniques [2-3] and those in gas explosions CFD codes FLACS [8] and FLUENT [10] has improved.

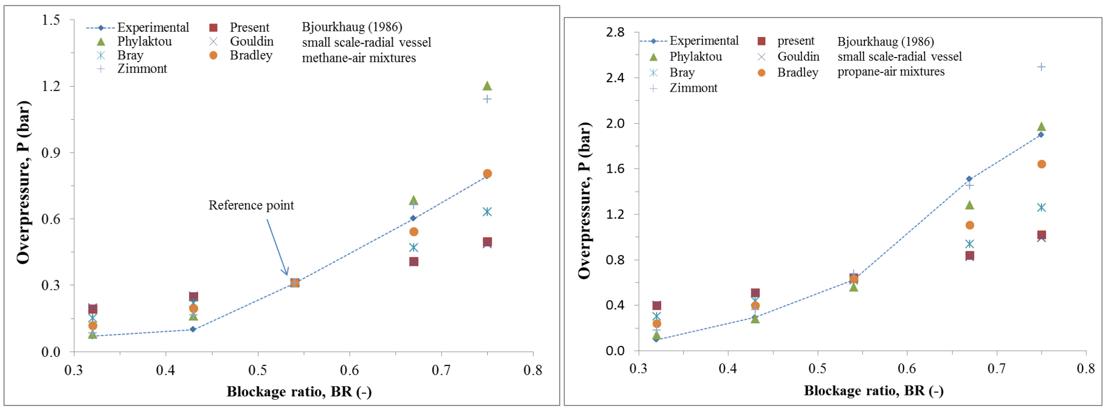

Fig. 4 Comparison between laboratory-scale experimental [11] and predicted overpressures (a) stoichiometric methane-air mixtures (b) stoichiometric propane-air mixtures.

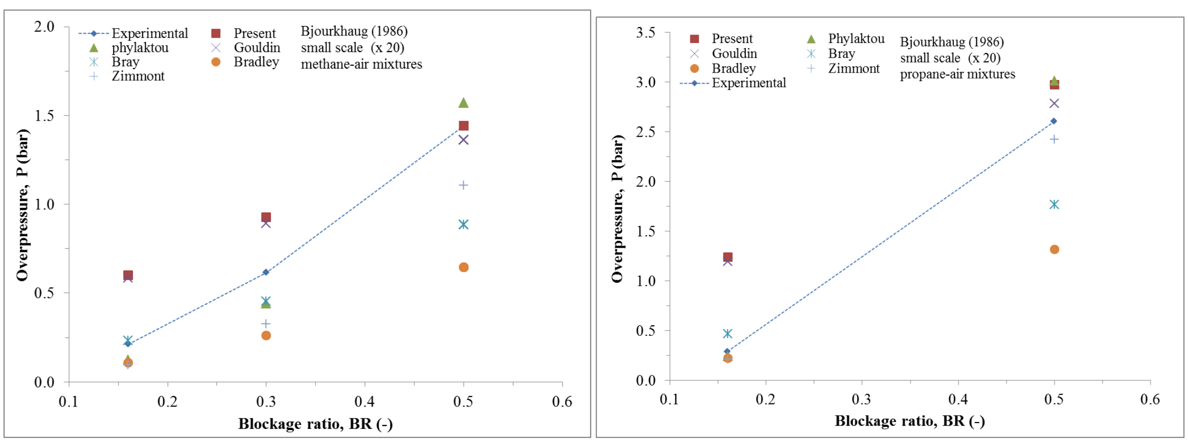

Fig. 5 Comparison between large- scale experimental [11] and predicted overpressures (a) stoichiometric methane-air mixtures (b) stoichiometric propane-air mixtures.

Conclusion

For a significant interpretation of results from small scale tests and for application to actual size explosion hazards, the understanding of the influence of ℓ which is determined by the presence of turbulence initiators (obstacles) in gas explosions is necessary. The S_T used in gas explosion scaling from small to large scale has a direct influence of ℓ. Thus, the present work measures S_T experimentally in gas explosions with two obstacles of variable spacing with a view to looking at its implication to gas explosion scaling. The newly obtained correlation is given as,

$$\frac{S_T}{S_L} = 2.99 R_{\ell}^{0.36}$$

The empirical S_T correlation shown above have demonstrated a dependence on ℓ which is significantly higher than most of the S_T models in the literatures. Even though, the variation in ℓ is small in absolute terms, the resultant estimates, mostly overpressures are significantly different and could make a barrier between safe and unsafe designs.

From the newly measured S_T, a blast overpressure correlation with explicit dependence on the geometric configuration, pressure loss characteristics (effectively the blockage ratio of the obstacles) and mixture properties was derived as,

$$P \propto \left[\left(C_T\sqrt{K}\right)^{0.54}\ell^{0.54}\right]\left[E^{2.54}S_L^{2.54}v^{-0.54}\right]$$

Also, the relevant S_T models used for gas explosion scaling and CFD codes (FLACS and FLUENT) were expanded to formulate gas explosion overpressure. The explosion overpressure correlations were validated against a limited suitable experimental data for both laboratory scale and a large scale that is 20 times bigger than the small scale. For both methane and propane-air mixtures, the calculated overpressures were in a close agreement with the experimental data especially for models with higher ℓ exponent. This agreement is very promising as it reveals that from using geometry at laboratory scale in the present research to calibrate an overpressure correlation, then the effects of different blockage ratios, gases and scales for the same overall geometry could be successfully predicted.

References

[1] Van Wingerden K, Pederson GH, Wilkins BA. (1994). Turbulent flame propagation in gas mixtures. Haz XII Euro Adv in Pro Saf. -: 249.

[2] Taylor P H, Hirst WJS. (1989). The scaling of vapour cloud explosions: A fractal model for size and fuel type. In: 22nd Int Symp on Combus (Poster Presentation), Seattle, USA.

[3] Catlin CA, Johnson DM. (1992). Experimental scaling of the flame acceleration phase of an explosion by changing fuel gas reactivity. Combust and Flame. 88: 15.

[4] Phylaktou HN. (1993). Gas explosions in long closed vessels with obstacles : a turbulent combustion study applicable to industrial explosions. PhD thesis, Uni of Leeds.

[5] Baines WD, Peterson EG. (1951). An investigation of flow through screens. Trans. ASME. 73:167.

[6] Phylaktou HN, Andrews GE. (1995). Application of turbulent combustion models to explosion scaling. Pro Saf and Env Protect. 73:3.

[7] Goulding FC. (1987). An application of fractals to modeling premixed turbulent flames. Combust and Flame,68: 249.

[8] Bray KNC.(1990). Studies of the turbulent burning velocity. Proc of the Royal Soc of London. Series A: Mathl and Phy Sci. 431: 315.

[9] Bradley D, Lau AKC, Lawes M. (1992). Flame Stretch Rate as a Determinant of Turbulent Burning Velocity. Phil Trans of the Royal Soc of London. Series A: Phy and Eng Sci. 338:359.

[10] Zimont V, Polifke W, Bettelini M, Weisenstein W. (1998). An Efficient Computational Model for Premixed Turbulent Combustion at High Reynolds Numbers Based on a Turbulent Flame Speed Closure. J. of Eng for Gas Turbines and Power.120:526.

[11] Bjoukhaug M. (1986). Flame acceleration in obstructed radial geometries. PhD thesis, City Uni London.

[12] Phylaktou HN, Andrews GE. (1994). Prediction of the maximum turbulence intensities generated by grid-plate obstacles in explosion-induced flows. Symp (Intl) on Combus. 25:103.

[13] Wardsmith AJ ed. (1971). Pressure Losses in Ducted Flows. London: Butterworths.