# Statistical Measurement of Critical Tube Diameter

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## 1 Introduction

Qualitative association of gaseous detonation phenomenon with "dynamic parameters" such as cell size and critical diameter has been a successful endeavor in detonation research for the last three decades.[1] Attempts to perform more quantitative correlation are complicated by the fact that soot foil records are difficult to characterize with a single cell dimension, often with considerable interpretation "by eye" required to extract data from a foil. Classification of cellular regularity, for example, is made by comparison of foils to those obtained by Strehlow in an early publication [2]. The technique of performing digital image analysis on foils [3,4] shows promise, but the nuances of foil preparation mean that it is unlikely that a given result can be reproduced by different researchers. The mechanism by which a detonation writes on a foil is still under investigation, and precisely what a smoked foil measures remains a subject of discussion.[5]

This paper proposes a new technique to provide an extremely precise quantification of detonation wave dynamics based on the critical diameter experiment. In the critical diameter experiment, a detonation wave emerges from a tube into an unconfined environment. The detonation either successfully transitions to a spherical detonation and continues to propagate or fails with the combustion front decoupling from the shock. The tube diameter which delimits these two outcomes is the critical diameter $d_c$. For a wide range of hydrocarbon/oxygen and hydrocarbon/oxygen/diluent (including hydrocarbon/air) mixtures, the critical diameter has been shown to be approximately 13 times the detonation cell size $\lambda$ ($d_c \approx 13\ \lambda$). For mixtures exhibiting highly "regular" cellular structure, such as hydrogen-oxygen (or acetylene-oxygen) heavily diluted with argon, the $d_c \approx 13\ \lambda$ criterion has been shown to break down, with the critical diameter being 25-30 $\lambda$.[6] This points to two different mechanisms of transition in critical diameter experiments, as discussed further in [7].

The current investigation seeks to measure critical diameter with greater precision than previously obtained via a statistically significant number of repeated measurements. This permits the "fuzziness" of the critical diameter to be measured. This can be understood by considering a mixture that has a critical diameter of, for example, 100 mm: If the tube diameter is reduced to 99 mm, will the detonation always fail upon emerging, and then if increased to 101 mm, will the detonation always continue to propagate upon emerging from the tube? Rather, it is anticipated that there is a distribution of probabilities around the critical diameter, where the outcome of an experiment continuously varies from 0% of repeated experiments resulting in detonation to 100% successful transition as the tube diameter is increased. Measurement of the width of the "sharpness" or "fuzziness" of this transition (this is more properly referred to as the "variance" or "statistical dispersion") may provide a new means to quantify the regularity or irregularity of detonation phenomenon.

While repeated experiments with different sized tubes is conceptually the most straightforward experiment to visualize, it is more convenient to vary other experimental parameters, such as mixture composition or initial pressure. For this study, the tube diameter is fixed and the pressure is varied. Since cell size and critical diameter are known to follow an inverse linear dependence when plotted on a log-log graph, it is possible to relate the variance of critical pressure with a fixed tube diameter to the variance of the tube diameter at a fixed pressure. Despite the fact that measurements like this have not been previously reported for gaseous detonation phenomenon, statistical measurements of critical gap thickness tests are routinely performed for condensed explosives using the so-called "Bruceton Up-Down" technique [8].

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## 2 Apparatus and Experimental Procedure

In order to perform this study, substantial effort needed to be focused on ensuring reproducibility of a given experimental condition (mixture composition, initial pressure, temperature, etc.). In order to verify the reproducibility of the experiment, the entire procedure was automated and driven from LabView (National Instruments) software. The software controlled evacuation of the chamber, filling and flushing the chamber with the detonable composition, setting the initial pressure, and firing the shot. The automated system also recorded data (pressure transducer signals) and analyzed results to determine "Go" or "No Go" upon transition to an unconfined detonation. In addition, LabView logged the temperature of the apparatus for every trial. The entire experiment was allowed to run autonomously, such that a very large sample of experimental data could be collected.

The mixture was prepared in a separate mixing reservoir in batches via the method of partial pressures. The mixture was allowed to mix for a period of days prior to use. The mixing reservoir was sufficiently large to contain enough mixture for approximately 100 experiments, such that a complete statistical "sweep" across the critical pressure could be performed for a single batch of mixture. This procedure ensured that the exact same mixture was used for each trial in a given sweep.

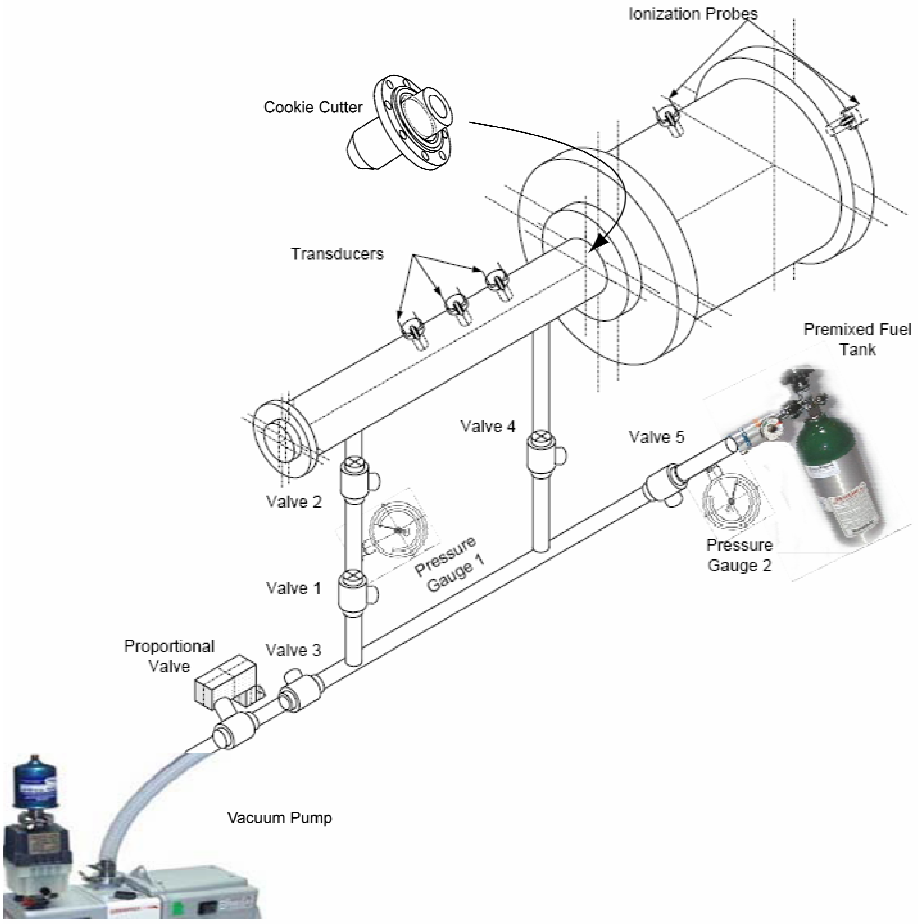


**Figure 1: Schematic of apparatus for measurement of critical tube diameter.**

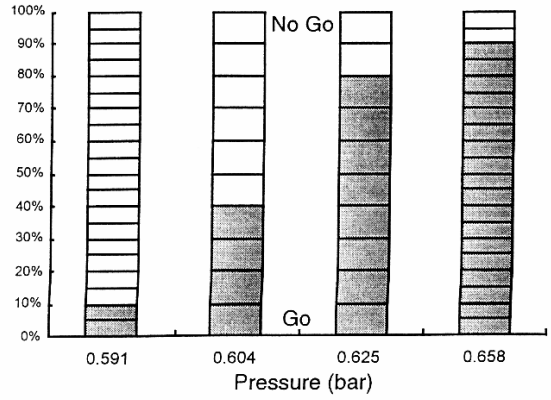


**Figure 2: Critical diameter results for $C_3H_8$+5$O_2$ with 20 mm diameter tube, with open squares denoting "No Go" and shaded squared denoting "Go" results.**

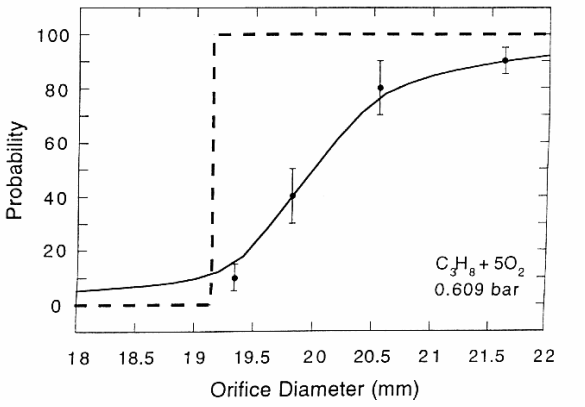


**Figure 3: Results from Fig. 2, shown as the probability of transition to unconfined detonation as a function to tube size, compared to the data (dashed) of Matsui and Lee [9].**

The uncertainly in mixture composition and initial pressure would result in a variation of critical diameter at least one order of magnitude smaller than the scatter actually observed. Thus, the scatter reported here is intrinsic to the detonation phenomenon itself, not scatter resulting from experimental technique. Note that the emphasis in this study is on precision, such that the relative scatter around the critical diameter can be quantified, rather than absolute accuracy of mixture composition and initial pressure.

The apparatus (Fig. 1) consisted of at 5-cm-internal-diameter detonation tube, 1.8-m-long. The tube was connected to a 19-cm-internal-diameter, 40-cm-long cylindrical test chamber. The detonation passed through a "cookie cutter" assembly before entering the test section to reduce the tube diameter to 3.8 cm. The mixture is ignited with an automotive-type spark, and the first meter of the tube is equipped with a Shchelkin spiral to assist transition to detonation. Pressure transducers along the tube verified the initiation of detonation, and a transducer in the test chamber determined if the transition to an unconfined detonation was successful from both the amplitude of the wave and the average velocity across the chamber. All results were an unambiguous "Go" or "No Go" with no intermediate cases.

## 3 Results

Preliminary results obtained with a smaller orifice diameter (20 mm) apparatus are shown in Fig. 2 where "Go" and "No Go" results are shown as a function of initial fill pressure of stoichiometric propane/oxygen for 60 experimental tests. Four different pressures were tested: 0.591 bar, 0.604 bar, 0.625 bar, 0.658 bar. As the pressure was increase, the percentage of "Go" results obtained increased from 10%, 40%, 80%, and 90%, respectively. In Fig. 3, these results are converted into a measure of the variance around the 50% critical diameter at a fixed pressure (0.609 bar) using the known relation between critical diameter and pressure from the data of Matsui and Lee [9]. This is contrasted with the usual view of critical diameter, as reported in [9] as a step function in probability, shown as a dashed line. The experimental variance is seen to be about 10% of the critical diameter, which is quite significant. This value could be reported as the "error bar" of critical diameter.

## 4 Discussion and Conclusions

By varying the initial pressure of a given mixture composition, the variance or statistical dispersion of the critical diameter can be measured with precision. The precision is limited only by the precision of the pressure transducer used to prepare the detonable mixture and set the fill pressure of the apparatus (which can exceed 5 significant digits), and by the number of experiments performed. The unprecedented exactitude of measurement of a dynamic parameter of detonation that this technique enables may permit a number of investigations to be carried out that are otherwise not amenable to experimental investigation. Issues such as:

- The "memory" a detonation has of its initiation or the duration of other upstream influences.
- Threshold of the effect of sensitizers and other additives to a detonable mixture.
- The role of statistical fluctuations along the detonation front in critical diameter vs. critical slot width experiments and the failure of the expected 2:1 scaling between these two parameters.

On-going experiments at McGill University are addressing these questions using the apparatus and technique discussed here.

## References

[1] Lee JHS (1984). Dynamic parameters of gaseous detonation, *Annual Review of Fluid Mechanics*, 16:331-336.

[2] Strehlow, RA (1969). The nature of transverse waves in detonations. *Astronautica Acta*, 14:539-548.

[3] Shepherd JE, et al. (1986). Analyses of the cellular structure of detonations, *21st Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1649-1658.

[4] Lee JJ (1995). Two-dimensional autocorrelation function analysis of smoked foil patterns, *Shock Waves,* 5:169-174.

[5] Inaba K, et al. (2005). Soot track formation by shock waves and detonations, *20th ICDERS*, Montreal, Canada.

[6] Desbordes D, et al. (1993). Failure of classical dynamic parameters relationships in highly regular cellular detonation systems, in *Dynamic Aspects of Detonations*, AIAA Prog. in Astro. Aero., Vol. 153, pp. 347-359.

[7] Lee JHS (1996). On the critical diameter problem, in Bowen R (ed) *Dynamics of Exothermicity*. Gordon and Breach, pp. 321-336.

[8] Dixon WJ, Mood AM (1948). A method for obtaining and analyzing sensitivity data. *J. Am. Stat. Assn.* 43:109-126.

[9] Matsui H, Lee JHS (1979). On the measure of the relative detonation hazards of gaseous fuel-oxygen and air mixtures. *21st Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1269-1280.