

Turbulence Behind the Front

Joseph E. Shepherd

Graduate Aeronautical Laboratories
California Institute of Technology
Pasadena, CA 91125 USA
jeshep@galcit.caltech.edu

Abstract

Four decades of experimentation have shown that all gaseous detonations are characterized by a peculiar large-scale compressible turbulence that is often referred to as cellular structure. A review is given of the folklore and science of cellular structure quantification which leads to that well-known but rather vague property: cell size. The review emphasizes the empirical connections between cell size, critical detonation parameters, and chemical kinetics.

Detonations as Turbulent Flows

Detonations in gases are notable for the characteristic turbulent flow [1] behind the main shock front. This turbulent flow has a unique type of large-scale structure which is associated with a quasi-periodic distortion of the detonation front. This large-scale structure is quite different than the large-scale vortical structures of low-speed turbulent flows. The large-scale turbulent structure observed in detonations is primarily due to the unstable interaction of compressible motions and exothermic chemical reactions. Although shear flow and vorticity are present in the turbulent flow behind detonation fronts, the most prominent features are the quasi-regularly-spaced weak shocks that propagate transversely to the main front, see Fig. 1.

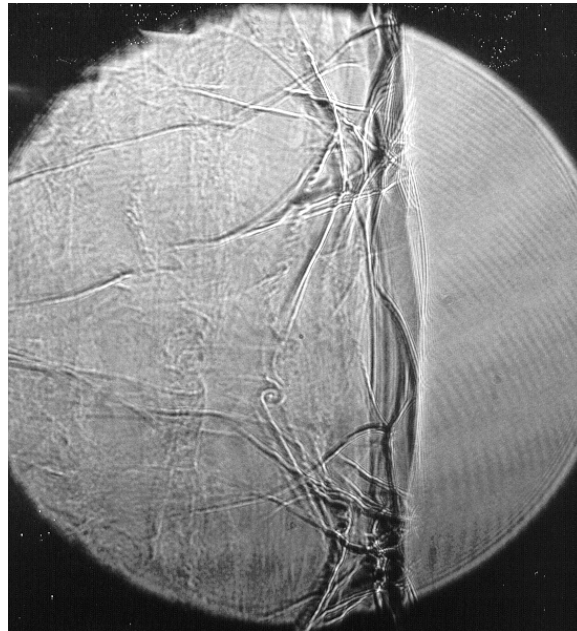


Figure 1: Schlieren visualization of turbulent structure of detonation fronts [2]

In detonation studies, the turbulent nature of the front is not characterized using the typical statistical description of mean and fluctuating quantities that is common to most fluid turbulence studies. Instead, the focus has been on the large-scale portion of the turbulent structure that is associated with the weak transverse shock waves. In particular, the standard measurement is to determine the dominant spatial wavelength λ or cell width that characterizes the transverse wave structure. Despite the seemingly crude nature of this characterization, such measurements have proven extremely valuable in ranking detonation hazards and correlating complex behavior such as diffraction.

Detonation Data

Detonation characterization has been largely an experimental and empirical activity. Experimental data has always been central to the field. Detonation data are widely scattered among monographs, journal literature, and institutional reports. Indeed, some valuable but obscure sources may be unavailable through ordinary literature searches. Data are often only available graphically and comparisons between data sets or between experiments and simulations requires digitizing graphs to obtain numerical values. Considerable effort can be spent gathering data for a comparison or during design of an experiment. We have created an archive [3] to minimize the effort required to locate and obtain numerical data, by compiling it in a single, accessible document. This archive is available electronically as well as in print-on-paper form. We invite all researchers to utilize this resource and to contribute data.

Measurement of Cellular Structure

The main tool for cellular structure measurement has been the soot foil technique. The distortions in the wave front are recorded by rearrangement of a thin layer of soot that is placed within the detonation tube or test chamber, see Fig. 2.

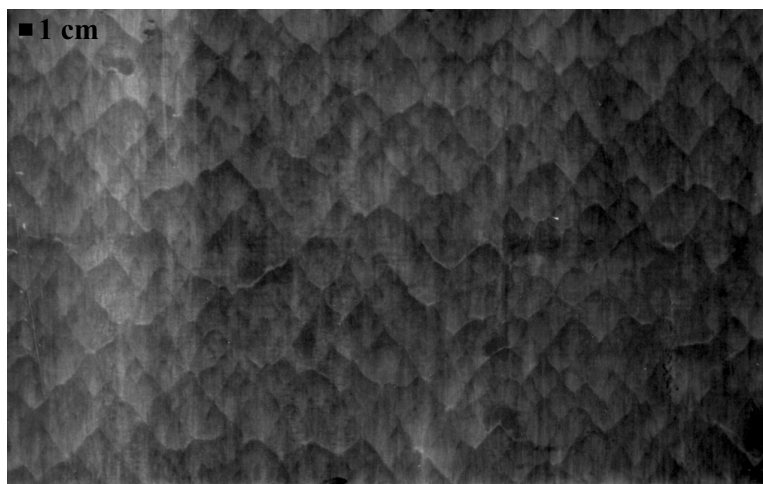


Figure 2: Recording of large-scale structures on detonation front by soot foil technique [4]

Despite extensive use since the turn of the century, the precise mechanism of soot rearrangement by the turbulence is not understood although it is known that the tracks are primarily associated with the intersections of the main shock front and the transverse waves. The key drawback of the soot foil technique is in the interpretation of the often extremely irregular tracks. Only in the case of special mixtures, high argon dilution in particular, is a unique cell size truly appropriate. In most cases, a range of cell sizes is visible and for exceptional mixtures, there are a hierarchy of sizes that defies simple characterization. Various image processing techniques and simple statistical measures have been proposed but have met with limited acceptance as a means of quantifying the statistical nature of the soot foil records. The lack of a bias-free method of characterizing cellular structure is a major shortcoming. Without such quantification, there is little hope for further refining and testing relationships between cell size and computed or measured detonation parameters. Cell width is an extraordinarily useful but extremely imprecise concept.

Critical Parameter Correlation

The motivation for many detonation studies is the analysis of the potential hazards associated with accidental initiation of detonation. Parameters such as minimum initiation energy, minimum tube diameter for propagation, and critical diffraction diameter have been correlated extensively [5] with cell width. More recently, these ideas have been extended [9] to problems such as transition from deflagration to detonation. Correlation of these parameters with cell size are essentially empirical in nature, notwithstanding the heuristic notions that are often put forward to justify the formulas. When these correlations are scrutinized it is apparent that there are substantial deviations from simple rules

like “ $d_c = 13 \lambda$ ” used to estimate critical diffraction diameter d_c . Attempts [6] to fix up these formula frequently appeal to some measure of cellular regularity, i.e., some properties associated with the spread in values of the track spacing on sooted foils. The imprecise character of both nominal cell width values and the “irregularity” is very limiting to progress in this area.

Chemical Reaction Kinetics

The finite rates of chemical reaction determine a characteristic length and time scale associated with the detonation front. Simple dimensional analysis suggests that any other length scale, such as λ , will be proportional to the chemical reaction zone length Δ . Explorations of this simple idea and by extension, correlation of other properties like d_c with Δ are [7, 8] able to provide useful guidance about the order of magnitude of λ and d_c , often sufficient for the purposes of hazard analysis. However, it is clear that this simple sort of linear correlation fails dramatically in some cases (Fig. 3) and that the constants of proportionality are not universal. Dorofeev et al (1998) have proposed an improved correlation that incorporates additional parameters such as activation energy and temperature. This idea gives significantly better predictive capability for the hydrogen-oxygen system and suggests the way to future improvements of this class of correlations.

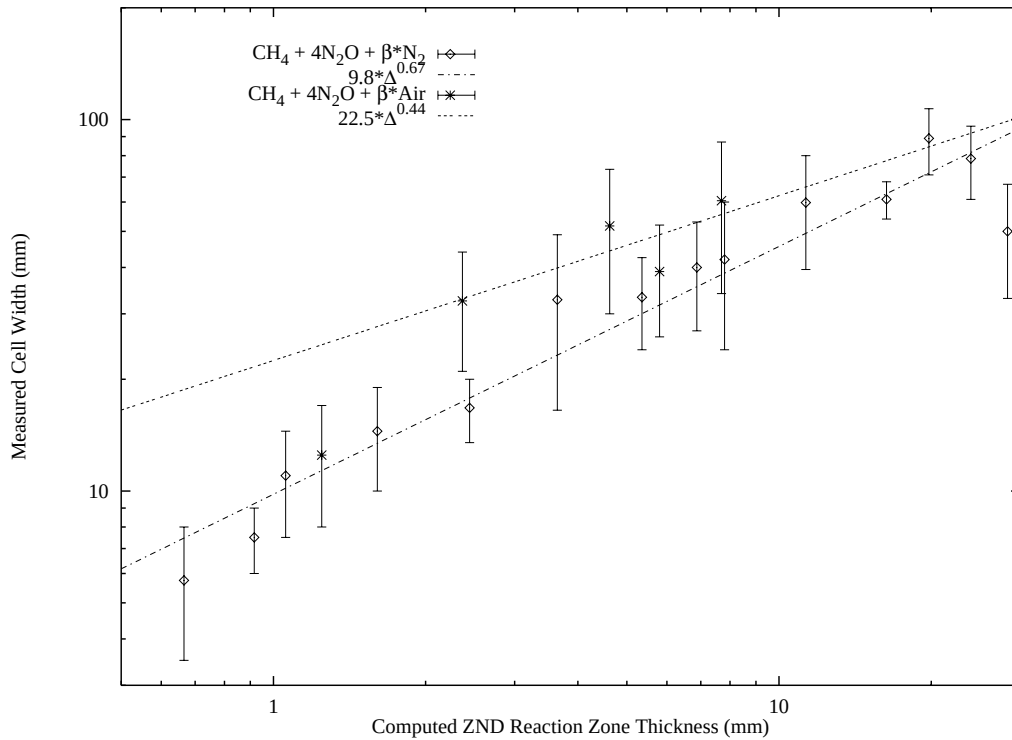


Figure 3: Nonlinear Correlation between cell width and reaction zone length.[4]

Summary

Detonation cell width is an extremely valuable concept but a rather imprecise one. In order to make further progress in this area, significant advances are needed in quantifying the turbulent flow behind detonation fronts.

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