

# The Role of Perturbations on the Shock-Flame Complex Leading to Detonation

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## 1 Introduction

Shock flame interactions have been widely studied due to their ability of amplifying the combustion process during an accident scenario. Following the ignition of a flame in a confined geometry, the flame accelerates until reaching a maximum speed, the Chapman-Jouguet (CJ) deflagration speed, at which point the flame structure consists of a lead shock followed by a turbulent flame which is trailed by a sonic surface. These flames are sensitive to disturbances, which may trigger an abrupt change in combustion regime resulting in the formation of a detonations[1–3].

A premixed flame can exhibits instability by itself due to the changes in the combustion dynamics without any external influence. A major contributor to such intrinsic instabilities is the Darrieus–Landau (DL) instability [4, 5], a hydrodynamic instability that causes all wavelength of perturbations on the flame front to grow over time. In subsonic combustion, this typically increases the flame surface area and thereby its energy release-rate. If the flame’s burning velocity enhances, the expansion of the burned gas generates stronger compression waves that may in turn reinforce the leading shock [3]. When a shock wave precedes the flame, the shock compression mechanism can either amplify or dampen the flame wrinkles, depending on the shock strength and shape [6]. In fact, the incident shock raises the pressure and temperature of the unburned reactants, preconditioning them and potentially increasing the flame’s turbulent burning velocity.

Poludnenko and colleagues [7] numerically investigated the spontaneous transition of turbulent flames to detonations in unconfined media. They observed that DDT arise from within the flame brush, although the controlling mechanism remained unclear. Rakotoarison [8] clarified the mechanism of transition to detonation in a 1D model with an arbitrary burning rate. When a flame burns faster than the maximum CJ deflagration, it modifies the upstream state to remain a CJ deflagration. This acceleration is associated with a substantial compression of the gas ahead of the flame, which is conducive to DDT. Hytovick et al. [9] experimentally explored the effect of flame-generated turbulence on the onset of DDT. Despite the experimental resolution being insufficient to pinpoint the mechanism, they speculated that flame acceleration could be due to vorticity production when flame-generated shocks interact with upstream gas. Perhaps the oldest explanation for self-turbulization of the flame is by the DL instability at scales much larger than the flame thickness.

To decipher the turbulent flame–shock complex, we propose a systematic study in which a small semi-cylindrical obstacle is introduced as a controlled disturbance to the shock–flame complex of a reactive mixture. The localized deformation of the flame and the resulting shock structure will help us address

two questions: 1. Does the imposed perturbation trigger a measurable strengthening or weakening of the leading shock? 2. Does this disturbance enhance the flame's burning rate, and if so, how does that feedback loop affect shock amplification? Our investigation examines the turbulent flame in the presence of a shock on a larger scale. Given that DL instability is not concerned with the structure of the flame, which only dampens the instability at sufficiently small scales, our aim is to quantify flame deformation beyond the size of a typical turbulent flame brush. We attempt to measure the rate at which the flame consumes the flow ahead of it and quantify how much the shock strengthens in response.

## 2 Experimental Details

The experiments were conducted in a 3400-mm-long thin rectangular shock tube, with height and width of 203.2 mm and 19.1 mm, respectively, as illustrated in Fig. 1. The tube is divided into three sections: detonation initiation, propagation, and test sections. The latter is equipped with glass windows for visualization purposes. The entire tube was initially filled with stoichiometric propane-oxygen, a very low- $\gamma$  and highly-reactive gas, at sub-atmospheric conditions and ignited using a hot tungsten wire at the left end. The use of mesh wires promoted the formation of detonation in the first section. Following this, the detonation wave propagated in the second section, where it reached a self-sustained state at the end of the propagation section, and its speed was confirmed to be in line with the estimated CJ detonation velocity using a pair of PCB pressure transducers mounted at the end of this section. The detonation then passed through a perforated plate, where its flame front decoupled from its leading shock. The plate had a high blockage ratio of 96%, such that the strength of the transmitted shock was primarily controlled by the mixture sensitivity, as explained in [10] and allows the generation of a more decoupled shock-flame system. Two series of experiments are presented in this paper. The first comprises a small semi-cylindrical obstacle with a radius of 1/32 of the channel height, located 165.1 mm downstream of the right edge of the perforated plate. In the second series, the obstacle was removed to monitor the evolution of the flow field in the absence of any controlled perturbation. The observations were visualized using the large-scale shadowgraph system ([11]). The exposure time was set to 440 ns, while the frame resolution was kept at  $1280 \times 272$  px. Six PCB pressure sensors were mounted along the top wall of the test section, recording the pressure data. The mixing tanks were first purged to a pressure of less than 40 Pa, and then the test mixture was prepared using the method of partial pressures and left to mix for more than 24 hours. The shock tube was evacuated before each test to a pressure of less than 80 Pa.

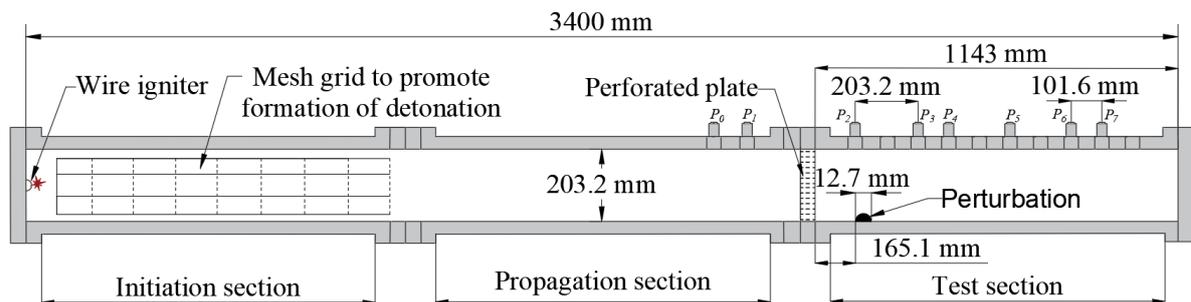


Figure 1: Schematic of the experiment setup in the shock tube; perforated plate has the configuration as stated in [10].

We have decided to first identify the deflagration regime of the shock-flame complex, as its strength significantly impacts the flow field progression. To pursue this approach, since there are already published measurements that distinguish the deflagration regimes based on the flame burning velocity [12], we chose an identical mixture and similar upstream obstruction for the detonation wave to transmit through.

### 3 Results

In the following, a range of initial pressures at ambient temperature were tested in the shock tube, both with and without the downstream semi-cylindrical perturbation in the visualization section. Fig. 2 compares the the shock-flame complex exiting the perforated plate at 8.27 kPa at the presence and absence of the controlled disturbance. At this fill pressure, the deflagration regime is above CJ deflagration (as reported by [12]). When the perturbation is absent (Fig. 2a) the flame deforms during the propagation. This is likely due to DL instability, which facilitates the propagation of laminar expanding flames through the natural formation of cells and wrinkles on flame front, increasing the flame's surface area. This larger surface area, in turn, raises the burning rate, creating a positive feedback loop that further drives the instability. When the perturbation is present (Fig. 2b), the flame is locally amplified by the interaction of shock and flame. This locally results in higher burning rate and local pressure increase. As a result of pressure waves originating at the combustion front, the local shock also amplifies. The subsequent focusing of the disturbed shock with the top wall reverses the shock shape. During this time, the flame undergoes much more deformation as in the non-perturbed case, which in turn contributes to the shock amplification. DDT is observed in the trough the flame brush, near the top wall. The timing of the DDT event appears to correlate with the arrival of the flame in the hot gases generated by the shock focusing. This observation is consistent with the findings of Xiao and Oran [13].

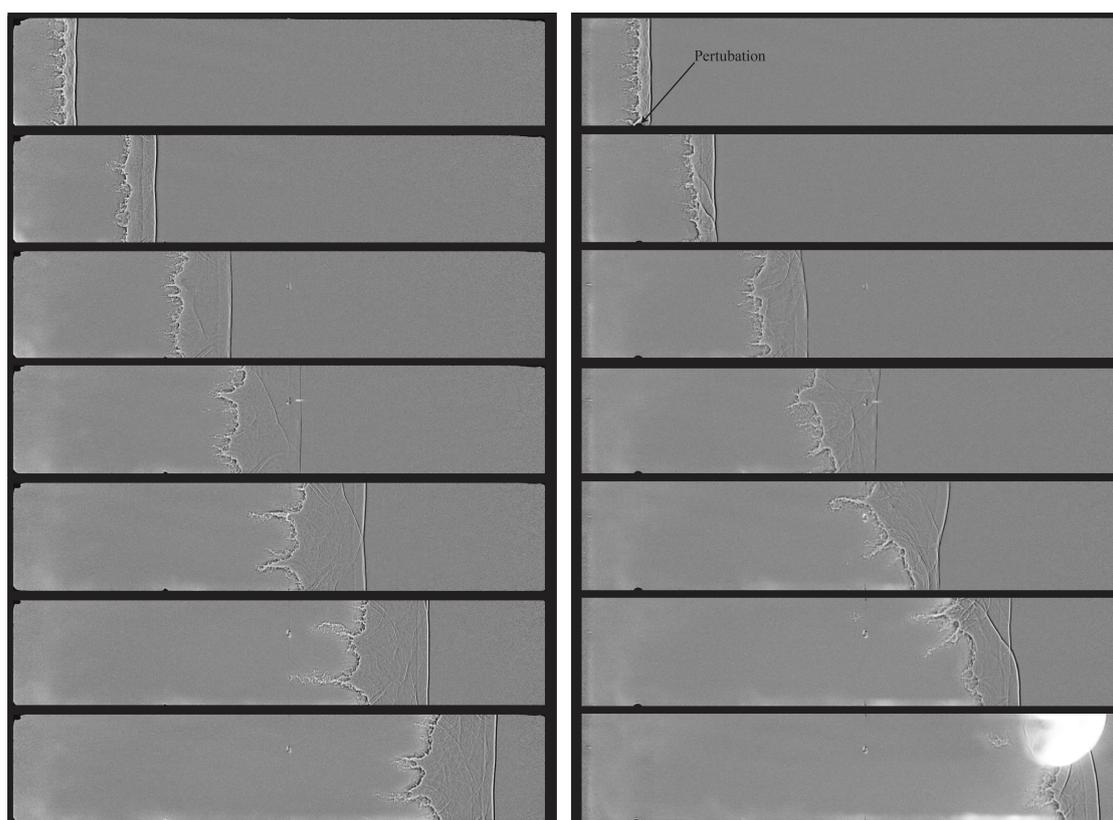


Figure 2: Shadowgraphs of  $C_3H_8-5O_2$  at  $p_0 = 8.27$  kPa a) without perturbation, b) with perturbation

With the increase of the pressure to 10.3 kPa, the non-perturbed flame also undergoes the same DDT process as in the perturbed case at 8.27 kPa (Fig. 2b). Fig. 3 shows how the flame spontaneously deforms during its propagation. DDT again occurs in the largest trough of the flame brush, near the zone of shock focusing, closer to the bottom wall. The mechanism of deformation is likely DL instability augmented by the compression of the non-planar lead shock.

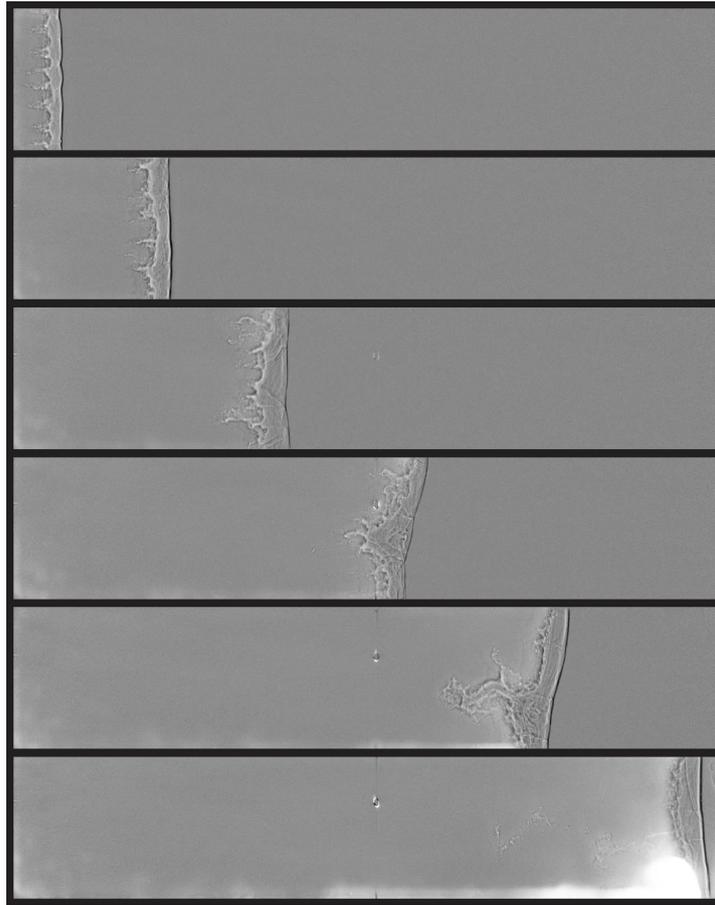


Figure 3: Shadowgraphs of  $C_3H_8-5O_2$  at  $p_0 = 10.3$  kPa within an unperturbed channel.

In contrast, as illustrated in Fig. 4 at the same pressure, the presence of perturbation gives rise to a more dramatic detonation formation. The immediate shock reflection behind the obstacle locally elevates the pressure and temperature and leads directly to a detonation wave.

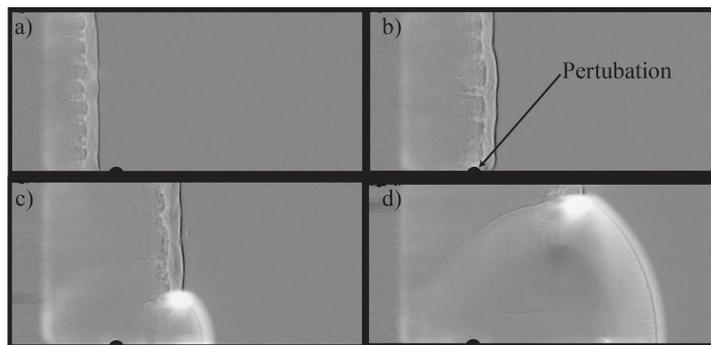


Figure 4: Shadowgraphs of  $C_3H_8-5O_2$  at  $p_0 = 10.3$  kPa within a perturbed channel.

Lastly, intermediate to the two regimes of DDT with perturbation is the regime illustrated in Fig. 5 at 9.3 kPa. Here, the shock reflection behind the small obstacle was not sufficiently strong to initiate a detonation, but ignited a large portion of gas. Then, this ignition provided enough support for the transverse wave, so that upon its reflection off the top wall, it led to DDT.

## 4 Discussion

We observed two distinct regimes of flame acceleration and DDT. In the presence of strong perturbations, local re-ignition of gas drove sufficiently strong shocks to establish the detonation immediately or after one reflection. A similar mechanism was identified by Bhattacharjee et al. [14], Maley et al. [11] and us in a companion study [15]. A slower regime of acceleration was observed in less sensitive mixtures. The experiments suggest that DL instability is responsible for the rapid deformation of the flame brush. The experiments also suggest a possible coupling between the flame deformation and the local shock amplification and dynamics. The locus of flame acceleration in the flame brush appeared to correlate with the locus of temperature increase by shock focusing. The DL instability with non-uniform upstream state owing to coupling with the shock motion will be further explored in the future and results will be reported at the Colloquium.

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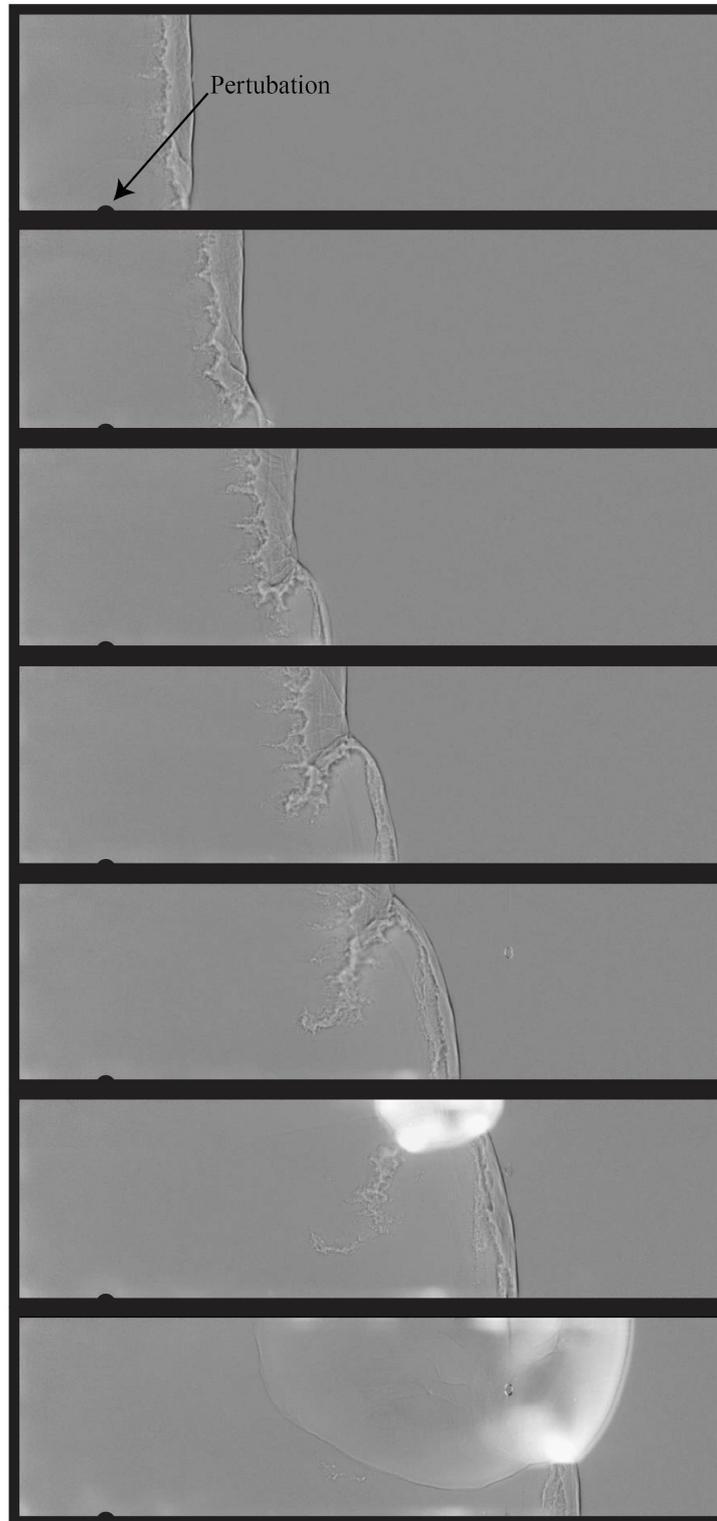


Figure 5: Shadowgraphs of C<sub>3</sub>H<sub>8</sub>-5O<sub>2</sub> at  $p_0 = 9.3$  kPa within a perturbed channel.