Interaction Between a Flame and a Rarefaction

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Introduction

The problem of whether an initially spherical, unconfined laminar flame can transition to detonation (DDT) remains unresolved. While there have been previous reports of unconfined spherical DDT [1-2], extremely sensitive mixtures of acetylene-oxygen were used, and DDT was suspected to result from small perturbations induced by the presence of the igniter. In other cases, DDT occurred so rapidly, that it did not permit any physical insight into the triggering instability. Most studies of DDT involve flames propagating in a confined channel, where a strong feedback mechanism of flame instability results from the turbulent flow over the channel walls induced by the expansion of the combustion products. Unconfined flames, on the other hand, generate only diverging pressure waves, which are lost to the surroundings due to the absence of boundaries. Therefore, the main issue involved in the study of unconfined DDT is to identify an instability mechanism that could trigger the exponential growth of the flame burning area. A possible candidate is the Richtmyer-Meshkov instability resulting from the interaction between the flame front and the rarefaction waves produced by the radiative cooling of the combustion products [3].

Early experimental studies of the Richtmyer-Meshkov instability [4] in flames involved the interaction of a shock wave with a flame front in closed tubes [5-8]. Markstein was the first to use a shock tube to control the strength of the shock wave. A flame was ignited in a tube section opposite to the shock tube. Observations of the interaction of the flame front with the incident and reflected shock waves were made. Markstein's results showed that the main consequence of the interaction between a shock wave and a flame was the formation of a funnel of unburned gas that extended into the burned region. Furthermore, the flame became more turbulent as the funnel approached the bottom flange. Later, safety concerns over industrial accidents motivated studies on vented gas explosions [9-10]. In these experiments, a flame was ignited in a closed vessel and after a certain amount of time, the chamber was vented to atmospheric conditions. The effects on the flame were the consequence of both an interaction with the rarefaction waves and the Helmholtz oscillations produced by the venting. The studies showed a growth of the flame front turbulence and, in the case of ignition at the rear wall, a funnel similar to the one described by

Markstein was also observed. More recently, unconfined DDT has received renewed interest due to the possibility that unconfined DDT occurs in type Ia supernovae [11]. Again, the role of rarefactions interacting with the reaction front may be an instability mechanism.

In the present study, the interaction between a flame and a rarefaction is investigated. The main goal is to simulate the conditions in which a rarefaction originating from the combustion products interacts with a flame, thus determining whether the resulting instability is sufficiently intense to result in DDT. The first series of experiments was aimed at vizualising the phenomenon, while the second was intended to investigate whether the interaction promotes DDT.

Vizualisation of the Rarefaction/Flame Interaction

A square tube was used which consisted of a 61 cm long test section and a 30.5 cm long low pressure chamber, both with an internal cross section of 12 cm by 12 cm. The top end of the test section was open prior to ignition to prevent pressurization. The test section was separated from the vacuum chamber by a perforated plate to render the expansion uniform along the cross section and a diaphragm was used to isolate the two tube sections. The test chamber was equipped with widows that covered two of its sides. The mixture was ignited with a weak spark 5 cm above the perforated plate. A plunger, which was activated by a solenoid valve, was placed in the low-pressure section and was used to rupture the diaphragm at the desired moment. The event was monitored by high-speed schlieren digital photography (1000 fps).

Prior to each experiment, the test section was filled with a lean propane/air mixture of $\phi = 0.8$ and the pressure in the low pressure chamber was lowered to approximately 0.5 atm. After flushing the test section for approximately 5 minutes, a flame was ignited at the center of the cross-section of the tube. After a certain delay, the diaphragm was ruptured and an expansion interacted with the upward propagating hemispherical flame. The ignition of the flame, the rupture of the diaphragm, and the trigger of the camera were synchronized using electronic time delays.

A typical interaction between a hemispherical flame and a rarefaction is shown in Fig. 1. The state of the flame front, after a certain amount of time past ignition ($t_{ignition}$ = 0 ms), is illustrated in each frame. The flame, just prior to the rupture of the diaphragm, is shown in the second frame, taken 62 ms after ignition. Between the second and third frames, the diaphragm is breached and the rarefaction waves have overtaken the flame front, resulting in a reduction in the radius of the hemispherical flame front. At t = 66 ms, a funnel of unburned mixture formed into the burned region. The last two pictures show the funnel continuing its downward propagation and a secondary instability developing at the tip of the funnel.

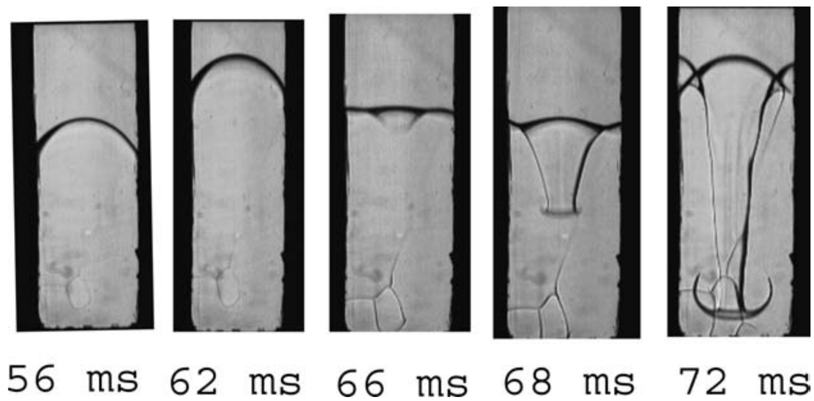

Fig. 1. Interaction of a quasi-unconfined hemispherical flame with an expansion fan

The effects of the interaction seen in the present study are very similar to the ones reported by Markstein [5]. It is seen that the flame is greatly distorted by the interaction with the rarefaction and the burning rate increases accordingly. Thus, the interaction between a rarefaction and an unconfined spherical flame is qualitatively similar to the classical shock-flame interactions. Therefore, this mechanism may play a significant role in the acceleration of a spherical flame and eventual transition to detonation.

Effect of the Rarefaction/Flame Interaction on DDT

For the second series of experiments, the apparatus was composed of the same components as before, except that the tube consisted a 2.5 m long circular steel tube with an internal diameter of 6 cm and there were no windows. The low-pressure section was 50 cm long. Ion probes distributed along the length of the test section were used to monitor the flame speed and a weak spark was used to ignite the flame, again near the diaphragm. The same sequence of events as for the first series of experiments applied, except that more sensitive propane/oxygen mixtures with nitrogen dilution (i.e., C_3H_8+5(O_2+1.5N_2)) were used so that DDT could be observed. To identify the effects of the rarefaction/flame interaction, a sequence of control experiments were also conducted in which the low-pressure section was replaced by flange, such that the test section was closed from both ends. In these control experiments, no rarefaction/flame interaction occurred.

An *x-t* diagram of the flame position can be seen in Fig. 2. It is seen that in the cases where a rarefaction interacts with the flame front, DDT occurs much sooner compared to the case where no interaction takes place. The interaction between the rarefaction and the flame has a turbulizing effect on the later, which in turn causes DDT prematurely when compared to the case when no such interaction occurred.

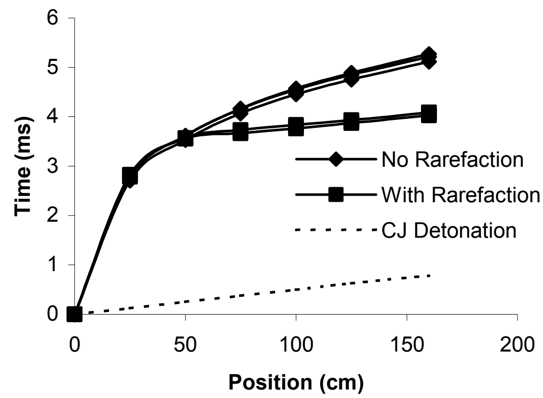

Fig 2. *x-t* Diagram of Flame Front Position for C_3H_8+5(O_2+1.5N_2)

Concluding Remarks

The present study investigated the effects of the interaction between a flame and a rarefaction. It was shown that a funnel of unburned mixture forms and propagates into the burned region, reminiscent of results obtained with shock waves interacting with flame fronts. The flame is highly distorted by the interaction with the rarefaction. Also, it was shown that the flame/rarefaction interaction leads to the premature DDT of the flame when compared with the case of no interaction. This suggests that this mechanism might be capable of triggering DDT in unconfined spherical flames.

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