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# Shock Wave Interaction with a Flame

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## Abstract

Shock wave/fire interactions initiated by high explosives have been historically demonstrated as potentially effective ways to control oil well fires or even forest fires in situations where conventional means cannot be applied. However, the mechanisms by which a fire can be extinguished by a shock wave are not well understood. A series of experiments have been conducted involving a moving shock front and trailing expansion flow, exhausted from the open end of a small shock tube, interacting with a simple small-scale flame – little research into this interaction has been conducted in the public domain. High-speed schlieren video of the transient flowfield was captured as the shock tube exhaust passed through a flame, causing a swift cessation of the combustion process. This visual data was used in to analyse the details of the instabilities which the shock induces in the flame, and the procedure of extinguishment during the flame's removal from the fuel source by the following jet. The results supplied new insight into the mechanisms of shock/fire interaction and allowed for a greater understanding of the means by which the flame is eventually extinguished. The limitations and suitability of this small-scale testing for studying applicability to large-scale fires are also discussed in the paper.

## Introduction

Shock waves from explosives are still routinely used to quench oil and gas well fires – a technique pioneered by McKinley in the 1920's and popularised by Red Adair in the latter half of the 20th century. In Kuwait in 1991, up to 70% of the well fires were extinguished using controlled charges [7]. Still, surprisingly little is known about the interaction between the shock wave and the fire. For instance, it is commonly reported that the explosion uses up or "sucks up" oxygen [7], but preliminary shock tube tests described in this paper confirm the hypothesis of Grishin et al. [4] that an actual explosion is not necessary in order for a shock to remove a flame from its fuel source and thus halt the combustion process. In essence, the shock front serves to impulsively move the pilot heat (existing flame) away from the fuel source, and is accompanied by an oncoming rush of expanding air which means that oxygen is temporarily not accessible. The degree to which induced Richtmyer-Meshkov instabilities – which arise when the interface between fluids of different densities is accelerated by a shock, leading to disruption and turbulent mixing - are instrumental in the extinguishing process is a matter of some debate [1,8], however it is likely that this fluid mixing occurs on a timescale much longer than the shock interaction and is one of several Mach-number-dependent factors influencing the effectiveness of the technique.

The present research effort, for which very preliminary findings are reported here, is aimed at creating a better understanding of shock/flame interaction fluid dynamics, with the eventual aim of investigating whether the technique can be applied to uncontrolled bushfires. Conventional means of fighting bushfires once they reach the uncontrolled stage have significant limitations. Aerial firebombing with water is not always effective due to dispersion at altitude, and supplying sufficient water on the ground can be challenging in rural areas; ground-level fire-fighting also places fire-fighters in potentially lethal positions. Containment of fires is often dependent on the arrival of more favourable weather conditions.

While oil and gas well fires are commonly successfully "snuffed" entirely by directional detonations, it is unlikely that the cellulosic material of a forest would be so quick to cease burning. However, smouldering fuel in the wake of the shock's passage would take time to re-establish into a fast-moving crown fire, during which time conventional aerial techniques can treat the area with water and retardants, and evacuations and new strategies could be implemented. With local loose fuel material knocked to the forest floor, the speed of progression of the fire and the propensity for it to re-form into a crown fire would be significantly reduced.

The idea of combating large-scale wildfires with shock waves is not new in itself – progress in advancing this technique has been made in recent times, most notably by Russian [2-6] and Chinese researchers [10], who propose using high explosives as a means of both halting the progress of a crown fire and stripping the trees of fuel which would otherwise carry such a fire at speed through the forest. In tests with a sufficiently large detonation, flame-out and cessation of spreading of the crown fire has been shown to take place, however the exact mechanism by which this occurs continues to be not adequately understood or explained in the scientific community.

The experiments described in the following sections establish a visualisation of a supersonic flow interaction with flame source under controlled conditions. The interaction was tested for simple candles and a Bunsen flame of varying intensity, to establish any relationship between the flame size and temperature and the effectiveness of the oncoming flow in extinguishment. The blast wave, generated by compressed air in a shock tube, has many of the same flow features and behaviour that would be expected from detonation of high explosives, and thus serves as a good approximation of the eventual intended full-scale application. While the broadly-spherical shock front travels supersonically downstream to the point of decay, the following exhaust flow is at a high-subsonic Mach number, and it is the latter aspect of the interaction which has the most profound influence.

## Methodology

The shockwaves were generated by using a conventional small-scale shock tube with the diffuser end removed such that the air was free to exhaust into the laboratory test range. The driver pressure was recorded and used to calculate the approximate Mach number of the shock, which was then verified against high speed video footage to account for deceleration and weakening downstream. The shock tube exit is a rectangle with dimensions of 44mm high and 47mm wide, which inadvertently produces a complex vortex ring and near-exhaust effects which are not the focus of this study but nevertheless affect the downstream flow conditions during the time-frame of interest shortly after the flame is extinguished, and will require further study.

The basic interaction between the exhausted flow and flame was visualised with a z-type schlieren imaging system [9] A schematic of the setup that shows the position of the equipment can be seen in Figure 1. The flame source was placed on the test rig to be in the direct line of fire of the shock tube. The flame source was located 510mm from the exit of the shock tube for the tests described here (though this was adjustable), and on the same plane as the shock tube exhaust such that the flame would bear as direct a "hit" as possible.

In these tests the flame was from a small candle, or Bunsen burner single open gas flame from natural gas. In the latter instance, both yellow "safety" flames and blue flames were examined to establish whether a hotter flame or different flame turbulence levels would result in any noticeably different behaviour.

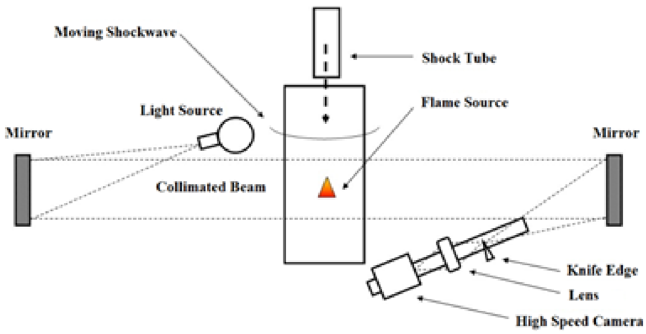


Figure 1. Schematic of the rig and schlieren setup. Not to scale.

A high speed video camera was used to take video of the interaction. The camera used was a Photron FASTCAM-ultima APX-RS. By using a high frame rate (>5000fps) the interaction could be analysed in slow-motion. The frame rate used to capture the images specifically presented in this paper was 12000 fps – high enough to capture the details of the flame being extinguished, but on the low side for imaging the shock passage.

The light source was a conventional quartz-halide bulb, with mirrors of approximately 1.5m focal length. Either single sharp knife edges or simplistic vertical tri-colour filters were used at the cut-off location. The buffering capability of the camera facilitated a manual trigger and a post-event selection of the pertinent section of video for further analysis.

Ambient conditions prevailed in the lab for all tests and were not expected to affect the tests significantly.

### Results

Figure 2 shows a sequence with a yellow Bunsen flame, after a shock wave of Mach 1.17 passed through the area of interest followed by a concentrated jet of expanding air exhausting from the tube exit. The total duration from frame a), where the exhaust flow first makes contact with the flame, to frame e), where combustion has completely ceased, is 0.003s. The flame is therefore less than 2 bunsen diameters away from its fuel source when it is fully extinguished. Frames b) through d) are of particular note, as they indicate the way in which the flame is compressed into what is effectively a single front – the portions of the flame refracted through the cutoff into blue and red zones are pushed together by the oncoming flow. Though the shock passed through the flame with essentially-negligible influence apart from inducing some extremely small-scale instability, the oncoming rush of expanding flow that follows has a significant effect, pushing the flame straight off the fuel source.

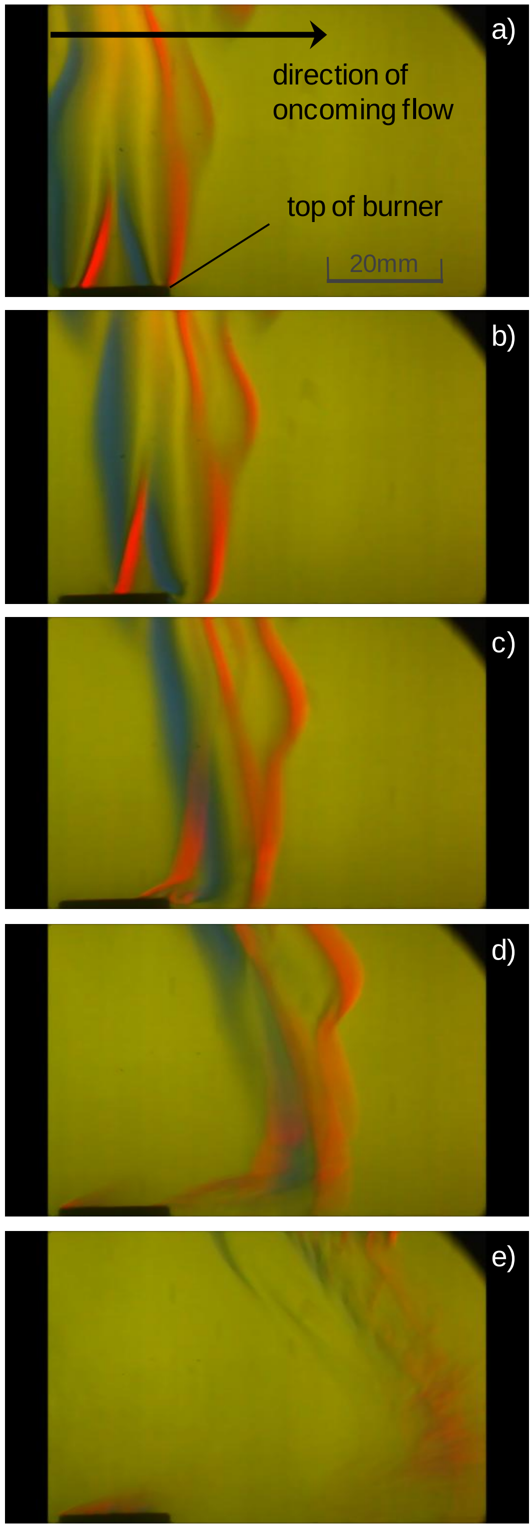


Figure 2. Sequence of frames from high-speed video spanning a period of approx. 0.003s, showing extinguishment of "yellow" Bunsen flame placed 500mm from the shock tube exit.

Interestingly, when the combustion has ceased and the majority of the expansion flow exiting the shock tube has passed through the test region, the remnant structures of the flame front, still represented by hot air and thus still visible in the schlieren images, break up in a fashion resembling a tornado. This indicates a high level of residual turbulence in the air from the strong vortices created at the shock tube exit. This brief phenomenon occurs at a near-static location within the field of view.

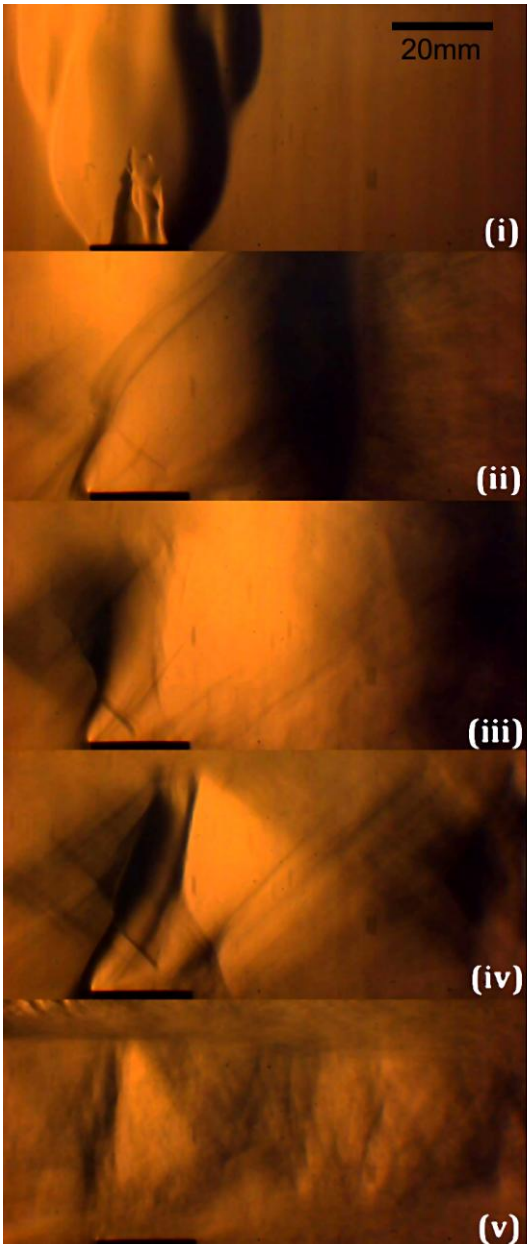


Figure 3. Sequence of frames from high-speed video spanning a period of approx. 0.002s, showing extinguishment of "blue" (hot) Bunsen flame when flame is placed 50mm from shock tube exit.

Figure 3 presents a similar sequence, this time featuring a hotter "blue" flame from the Bunsen burner, which can be clearly seen as the smaller central flame structure above the burner lip. In this instance, the flame was placed 50mm from the shock tube exit in order for a strong shock wave and supersonic-dominated flowfield to interact with the flame. Here, the flame is extinguished near-instantly as the initial shock wave meets it, with the remainder of the shock tube exhaust following closely and at supersonic velocity, forming an intricate shock pattern around the Bunsen. The process is more immediate and violent than the situation where the flame was placed 500mm away, with the flame comprehensively removed from the source and any remnant fuel pushed far from the field of view.

The image sequence presented in figure 4 shows shock/expansion interaction with a series of three candles. Although the flame in this instance is distinctly laminar, the array of candles presents a scenario that is somewhat representative of a crowning wildfire where multiple flames and fuel sources are present in close proximity. For a shock tube exhaust identical to that used to produce the images in figures 2 and 3, it is possible to observe flow features both similar to and different from the tests with the single Bunsen burner.

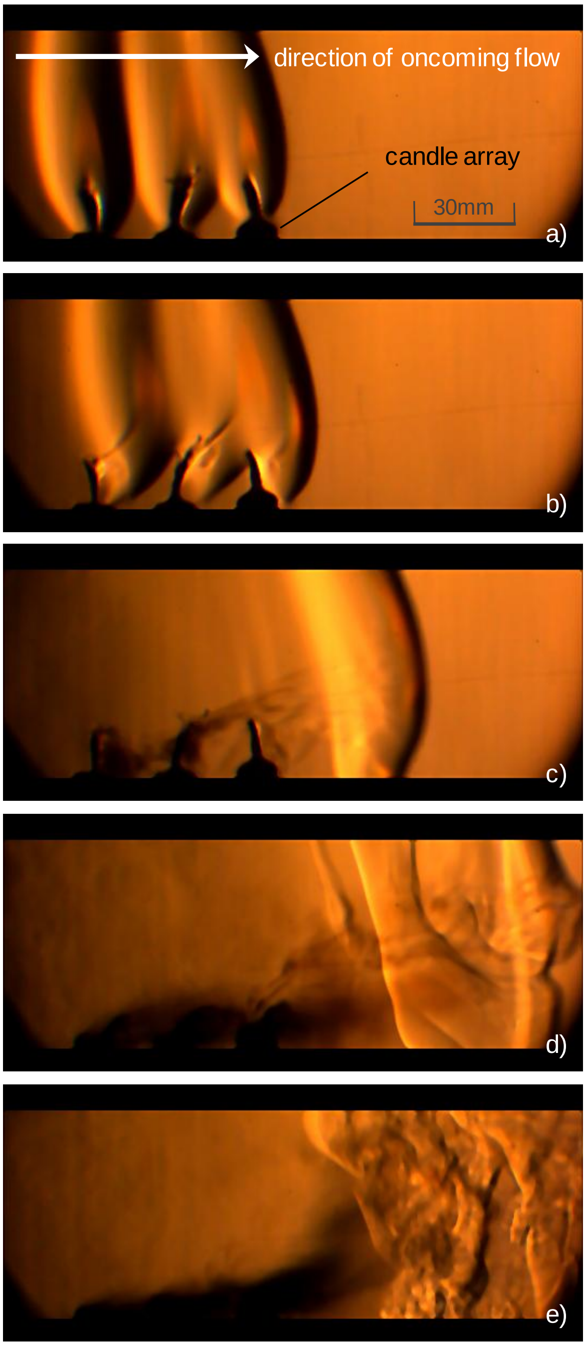


Figure 4. Sequence of frames from high-speed video spanning a period of approx. 0.003s, showing extinguishment of candle array when candles are placed 500mm from shock tube exit.

It is clear that a broadly similar process occurs, whereby the rush of expanding flow in b) is the primary source of impulse for the flames moving off the first two candles – at this moment, that flow has only just reached the third candle, and it is clear that the sequential shift of flame off fuel source (the wicks) has begun. By image c), all three flames have combined into a single flame front, which is still combusting downstream of the candles and at the fore of the expansion flow. Flame breakup follows in frame d), less than 1 millisecond later, due to a lack of fuel and also the rapid lateral spread of the flame due to the oncoming flow. In frame e) this process reaches its conclusion as the hot air from the flames is dispersed in what is now a much lower-velocity flowfield, and the hot air begins to be drawn back towards the shock tube, as in the other examples, due to low pressure vortices accompanying the shock exhaust jet.

## Conclusions

Preliminary experiments have been conducted which were designed to investigate the mechanisms by which a shock wave, in this case exhausted from a shock tube, might extinguish a flame as has been reported in literature. It was shown that the shock wave itself has little discernible influence on the flame (be it a candle or from a Bunsen burner) when the flame was significantly downstream of the tube exit, other than the introduction of an instability at a timescale much faster than that at which the flame fluctuates naturally. The expanding flow following the initial shock is the dominant means by which the flame is impulsively removed from its fuel source, after which the flame disperses rapidly and combustion ceases – at this flame size, this process happens at the millisecond scale, and within only a few hundred millimetres of the fuel source, indicating that a rapid deprivation of fuel as a result of physical displacement is the primary mechanism by which the flame is extinguished. When the flame was placed close (50mm) to the tube exit, the shock wave and jet arrived together and extinguished the flame with greater swiftness, the overall effect being the same albeit with a lingering shock structure due to the continued supersonic nature of the exhaust jet right at the tube exit.

Work is continuing at laboratory scale to investigate, parametrically, the role of shock strength/Mach number, the influence of the distance of the flame from the shock tube, and a better characterisation of other variables affecting the interaction. Studies are currently underway utilising high-frequency pressure transducers to record the evolution of the flowfield, allow exact determination of Mach numbers and pressures, and provide information on the decay of the exhaust with time. The introduction of a ground plane and an improved schlieren setup is expected to allow the visualisation of the shock/Mach stem travelling along the surface and better approximate the desired application.

With a longer-term view to establishing whether the technique can be used effectively at a large scale for an actual bushfire, work on the project will continue in 2013 in collaboration with the United States Naval Surface Warfare Centre at Indian Head, Maryland.

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