Application of heterodyne velocimetry and pyrometry as diagnostics for explosive characterisation

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Abstract. The results of four cylinder tests performed on two batches of the HMX based explosive EDC37 using a new suite of diagnostics are described. Heterodyne laser velocimetry (het-v) and pyrometry were fielded for the first time on cylinder tests within AWE. Pyrometry gave a measurement of the temperature of the detonating HE of 2600-3485 K. Sixteen channels of het-v were fielded and provided high fidelity expansion data at distances of up to 30 mm. High speed framing camera images were obtained and show no signs of cylinder break up or spallation until distances greater then 35 mm. The het-v expansion data made it possible to resolve up to 8 shock reverberations in the wall as it expands. The expansion of the cylinder wall was recorded both before and after steady state detonation was reached and the results compared. Het-v probes were fielded at different angles to the expanding cylinder wall allowing both the vertical and horizontal expansion velocity to be determined. The extra information that these cylinder tests yielded will allow for more accurate code validation and determination of the equation of state of the explosive products.

1. Introduction
The cylinder test is an explosive trial that measures the ability of an explosive to move metal. The results from this test allow the coefficients of the Jones-Wilkins-Lee (JWL) analytical equation of state (EoS) for a given explosive to be determined. The derived JWL EoS is then used to model explosive performance using hydro codes. Increasing the accuracy and reproducibility of cylinder tests allows for more accurate coefficients to be derived. In order to test the performance of a hydro-code model it is important to gather as much information from the cylinder test as is possible.

This work directly compares traditional cylinder test diagnostics used with het-v, a.k.a photon Doppler velocimetry (PDV). This comparison will provide for read across to existing legacy data.

2. Experimental Details
The cylinder tests performed consisted of a EDC37 (91% HMX) [1] cylinder of high explosive encased in an open ended copper tube that was initiated from one end with an RP-80 exploding bridge wire detonator. As the detonation wave propagates down through the cylinder it causes the cylinder walls to expand. The velocity history of the expanding cylinder is measured either directly or indirectly. Traditionally the expansion of the cylinder was recorded using a total internal reflection prism with a streak camera and electrical contact probes [1]. These measure the time of arrival of the cylinder as a function of distance and from this a velocity history of the expanding cylinder is produced. In addition to the traditional diagnostics these trials utilised 16 channels of heterodyne velocimetry (het-v) [2] to record the velocity of the expanding copper cylinder with time. Figure 1 is a diagram of the experimental geometry used for these four experiments.
3. Results

3.1. Cylinder Expansion

One of the main objectives of this trial series was to compare the results obtained by the het-v diagnostic to the traditionally used prism and probe boards. The prism measures the expansion of the copper wall over the first 6 mm. Figure 2 shows the expansion as measured by a prism on one of the experiments compared to one het-v trace from each of the four experiments. It shows that there is good agreement between the velocity as a function of expansion as measured by the prism and the het-v, it also shows that there is good agreement across all four of the experiments. This shows that the performance of the two batches of the explosive is the same. The jumps in velocity that can be seen are due to the shock ringing in the copper as it expands. With the traditional prism diagnostic it is possible to see up to three reverberations, with het-v it is possible to resolve up to eight.

Figure 2. The early expansion of the copper cylinder as measured by the early motion prism on one trial (black line) and one het-v trace from each of the four trials (coloured lines).
The probe boards are traditionally used to measure the expansion of the copper cylinder over the first 20 mm of expansion. Figure 3 compares the expansion as measured by one board from each of the four trials and one het-v trace from one of the trials. It shows that there is good agreement between the boards and the het-v across the whole range that the boards measure. The reason for not showing more het-v traces is to aid the comparison to the boards. All the het-v traces obtained once steady state had been reached showed good agreement across all four trials. Het-v has the potential to measure the expansion beyond the range of the traditional diagnostics as shown in figure 3. Framing camera images taken on these experiments indicate that it should be possible to perform measurements to beyond 40 mm of expansion.

![Figure 3](image.png)

*Figure 3.* The expansion of the copper cylinder as measured by one board from each experiment (symbols) and a het-v trace from one experiment (solid line).

Unlike the traditional diagnostics het-v probes directly measure the velocity along their axis. The traditional means rely on aggregating data from several points at different distances from the cylinder. In order to avoid any effects of asymmetric expansion these different points are at different heights directly in line with each other, this means that a large region of the cylinder must be at steady state in order to perform a full measurement.

Because het-v does not require a large region of the cylinder to be in the same state to measure the velocity it is possible to record the expansion of the cylinder at regions before steady state detonation has been reached. This is valuable as it can be used as extra data to test the hydro code modelling. It can also be used to help identify when a steady state is reached. This is a more sensitive measure than the velocity of detonation as it relies on the shape of the detonation wave front as well as its velocity. Figure 4, shows the velocity as a function of expansion as measured by het-v probes at different distances from the detonator. The trace closest to the detonator shows a higher initial jump off velocity, this is consistent with the larger boundary angle that the pre steady state detonation wave will have, it also shows a spike in the velocity in the middle of the second reverberation. This spike reduces in size as steady state detonation is approached. The exact source of this second reverberation is unclear although it could be an artefact from a spall and recollection. Further work will be undertaken to investigate this phenomenon.
The velocity of the expanding cylinder over the first 6 mm of motion as measured by het-v probes at different distances from the detonator on one of the experiments.

By fielding het-v probes at different angles it is possible to extract information about the vertical component of the cylinder expansion. As Briggs showed [3] if a probe is placed so that it is at 30° to the direction of the motion then the velocity that it records will be $v_{\text{meas}} = v \times \cos(30)$. If there were only expansion of the cylinder at 90° to its original orientation then a probe placed at 30° from this expansion would observe the $\cos(30)$ relationship.

Figure 5, shows the velocity as recorded by a probe angled 60° to the cylinder (30° from the 90° probes) compared to $v \times \cos(30)$ from a probe at 90°. The angled probe records a higher velocity than would be the case if there were only expansion 90° to the cylinder. The difference is due to the vertical velocity of the cylinder wall contributing to the velocity measured by the 60° probe. Due to the orientation of the experiment it is not possible for these contributions to be from any other velocities.

Figure 5. The velocity of the expanding cylinder as measured by a probe angled 30° off axis from the majority of probes (black line), the velocity measured by an on axis probe multiplied by $\cos(30)$ (red) and the vertical velocity of the cylinder wall derived from these traces (blue). Inset in the plot is a diagram illustrating the probe and velocity directions.
The vertical velocity component, shown in figure 5, contains some inherent errors. Due to the experimental geometry fielding a probe at an angle has the effect of stretching the velocity trace in time; this means that at certain times the shock reverberations don’t match up giving a misleading value for the velocity. Stretching the trace also leads to a slightly higher value for the vertical velocity being derived. Probes were fielded at 10°, 15° and 20° in addition to the 30° shown here. There was no trend in the vertical velocity obtained with changing the angle as would be expected if this stretching error were a dominant effect. The average value obtained after 8 µs for the vertical velocity was 130 ms\(^{-1}\) with a standard deviation of 53 ms\(^{-1}\). The main source of error on this measurement was uncertainty in the angle of the probes, this has been refined on subsequent experiments. In order for this technique to work the detonation must be at steady state.

3.2. Pyrometry

The pyrometry set up for these experiments consisted of optical fibres looking through a LiF window that was in intimate contact with the explosive at the bottom of the cylinder. The light collected by each fibre was passed through a band pass filter and recorded by a detector. The intensity of light at each specific wavelength was used to derive a temperature using the grey body assumption. The emissivity of the detonation products was not known so the temperature was calculated for both an emissivity of 1 and for an emissivity of 0.5. Framing camera images of the trial show that the detonation products are sooty, black and opaque, for this reason we believe that the emissivity will lie within this range. Four temperature measurements were successfully made during this trial series and can be seen in table 1. The first three measurements were made on the same experiment the fourth on another.

Table 1. Temperatures measured at different wavelengths.

| Temperature / K (emissivity 1) | Temperature / K (emissivity 0.5) | Wavelength / nm |
|-------------------------------|---------------------------------|-----------------|
| 2873                          | 3485                            | 1300            |
| 2782                          | 3375                            | 1400            |
| 2516                          | 3052                            | 1550            |
| 2600                          | 3154                            | 1300            |

The spread of values, particularly between the two 1300 nm results, indicates the level of error in the measurement on top of the error due to the unknown emissivity. Despite this the data sheds light on a previously unmeasured quantity for EDC37. Theoretical temperature estimates for the bulk detonation temperature ranged from 1000-3500 K.

4. Conclusions

Het-v has been shown to produce data that is directly comparable to that obtained by the traditional diagnostics over the range that the traditional diagnostics cover and to provide data beyond this range. In addition is has been shown to produce higher fidelity data which reveals features that were not possible to resolve before. Due to the point like nature of the het-v probes it is possible to investigate the expansion of the copper before steady state has been reached.

Het-v data at different angles has been used to obtain values for the vertical component of the expansion of the cylinder wall. This will allow for better calibration of hydro codes and along with the improved fidelity described above could ultimately lead to more accurate parameters for the JWL EoS being derived. Developments in this area will concentrate on reducing the error and increasing the sophistication of the analysis.

Pyrometry has been used to provide an initial temperature estimate for the detonating products. Spectroscopy will be performed on future experiments to investigate if the grey body assumption applies to the detonating products.
References
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