Temperature Measurements in a Multiphase Fireball

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1 Introduction

Detonation of a homogeneous high explosive charge generates high pressure and temperature combustion products and a propagating decaying blast wave. The combustion product gases rapidly cool as they expand adiabatically, whereas the shock heating of the atmosphere surrounding the combustion products generates a relatively long lasting zone of air at elevated temperatures. For oxygen deficient explosives, mixing and afterburning of the condensed carbon with this shock-heated air will result in condensed reacting carbon that may have a different temperature than nearby gases. The detonation of a heterogeneous high explosive containing reactive metal particles generates a multiphase fireball in which the particles and gas are, in general, not in thermal equilibrium. The temperature of the burning particles may be relatively constant whereas the temperature of the combustion product gases will vary rapidly. In addition, the temperature of the air surrounding the combustion products will be augmented by heat transfer from the particles. The coupling between the energy released by metal combustion and the strength of the blast wave will depend on the proximity (and number density) of the particles to the blast wave and the rate of energy transfer to the local gas environment. In the near-field, instability of the combustion products interface as well as the particle cloud will result in large spatial variations in the gas and particle temperature fields. Most previous work has used non-intrusive optical techniques (pyrometry, spectrometry) to infer the temperature of condensed and gaseous species within the fireball [1-3]. In the present work, in-situ temperature measurements are made within the near field of homogeneous (nitromethane, NM) and heterogeneous (NM with aluminum particles) explosive charges. The results are compared with earlier pyrometric measurements of the temperature of the condensed species within the fireball.

2 Computational Results

Computations were carried out with the Chinook multiphase code [4] to model the response of a finite-sized thermocouple to the flow field generated by the detonation of a 1 kg NM charge (12.3 cm dia). The results shown in Fig. 1, for a 127 μm (5 mil) K-type thermocouple illustrate two points: i) due to the thermal inertia of the thermocouple, the thermocouple temperature lags behind the local gas temperature, and ii) the thermocouple temperature approximately equals the gas temperature only when the thermocouple temperature exhibits a local maximum. The 2D calculation does not accurately capture the small-scale turbulent mixing at the combustion products interface and hence the

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temperature results are not expected to be quantitatively accurate. Calculations were also carried out for a 12.3 cm dia charge containing NM saturating a packed bed of spherical (54 µm) aluminum particles. The results are also shown in Fig. 1 and indicate that while the maximum radius of the combustion products is about 0.8 m, the particles quickly penetrate the combustion product interface into the shock-heated air, but generally remain behind the leading blast wave.

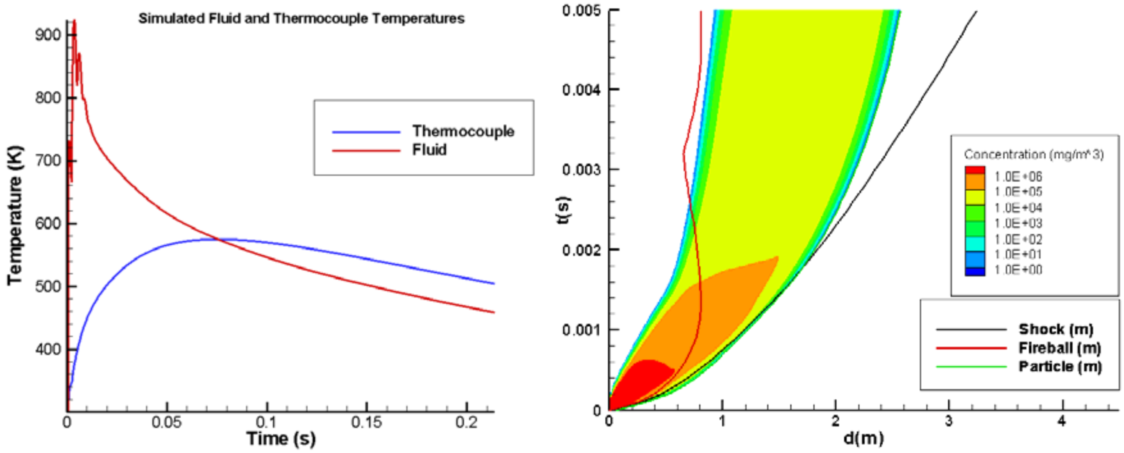

Figure 1. Left: Computed thermocouple and gas temperatures at R = 1.2 m, for the detonation of a 1-kg NM charge. Right: Computed trajectories of blast wave and combustion product interface with particle concentration profiles for detonation of 12.3 cm dia charge containing NM with 54 µm spherical aluminum particles.

3 Experimental

For the majority of the trials 127 µm (5 mil) K-type thermocouples were used. The mounting of the thermocouples is shown in Fig. 2. For several trials 25 µm (1 mil) and 51 µm (2 mil) gauges were used, but typically did not survive the event. Details of the charge preparation and experimental procedure can be found in [5]. The spherical aluminum particles were obtained from Valimet Inc. The results presented were for H-50 particles with an average size of 54 µm by mass.

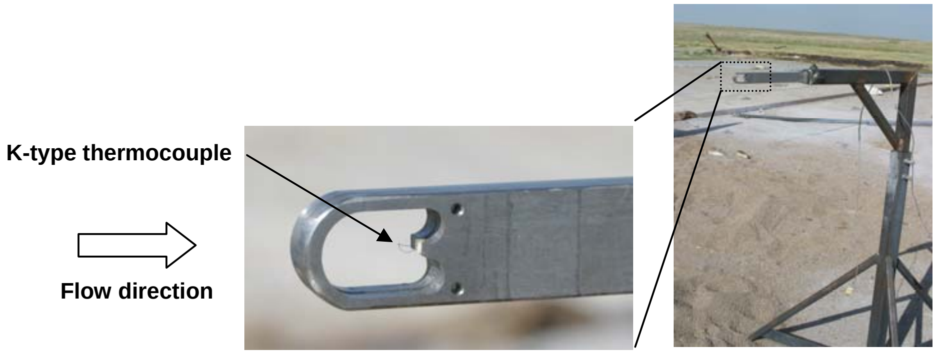

Figure 2. Close-up of thermocouple mount and mounting on stand for field experiments. Thermocouple is protected from direct impact with a particle, but exposed to the ambient flow conditions. Three different sized K-type thermocouples were used (25, 51, and 127 µm). Maximum (melting) temperature of K-type thermocouple is about 1400ºC.

4 Results and Discussion

The temperature measurements for the homogeneous (NM) and heterogeneous (NM/Al) charges are shown in Figs. 3 and 4. In each case, photographs of the fireball development at the same time intervals are shown, together with an example of the thermocouple measurements, and a compilation of the maximum thermocouple temperature (which corresponds approximately to the instantaneous local gas temperature) as a function of time and distance. Several observations can be made from these figures. For the NM charges, the temperature measurements were taken within the zone of turbulent mixing of the fuel-rich combustion products and shock-heated air. Due to the spatial temperature nonuniformities resulting from the Rayleigh-Taylor jet formation in this region, the maximum temperature could occur at any of the three distances used (1.2, 1.5, and 1.9 m), depending on the trial. A maximum gas temperature of about 800ºC occurs at times on the order of 100's of milliseconds, which is considerably lower than the temperature of the condensed products (soot) of 1625±150ºC that was measured earlier with optical pyrometry at times on the order of 10 – 100 ms [2]. The thermocouples are too slow to respond to the very high shocked-air temperatures observed by pyrometry at early times [1,2].

For the heterogeneous charges containing 54 µm spherical aluminum particles, the gas temperature in the air surrounding the combustion products remains at elevated levels for long durations, e.g., temperatures of above 1000ºC were recorded for up to 0.5 s at even the furthest distance of 1.9 m. The gas temperatures are still considerably lower than the temperature of the burning particles, estimated earlier with pyrometry to be 2400±200ºC at times on the order of 10's ms [2]. Large spatial nonuniformities in the gas temperature were recorded. This is due to several factors. First, due to the large mass loading of aluminum particles (79±1% by mass), in many cases the expanding cloud of aluminum particles did not ignite uniformly throughout the cloud, leaving pockets of unburnt particles that burn out over long timescales. Secondly, in addition to the RT-instability of the combustion product interface, the particle cloud is also unstable and typically forms coherent clusters of particles. The local gas temperature attained depends on whether a burning jet of particles engulfs a thermocouple gauge (or not). Finally, it should be noted that additional experiments were carried out with inert particles (both glass and iron particles, ~100 µm in dia, were used). In both cases, the inert particles acted as a very effective heat sink for the thermal energy in the combustion products; in all experiments the gas temperatures recorded never exceeded 100ºC.

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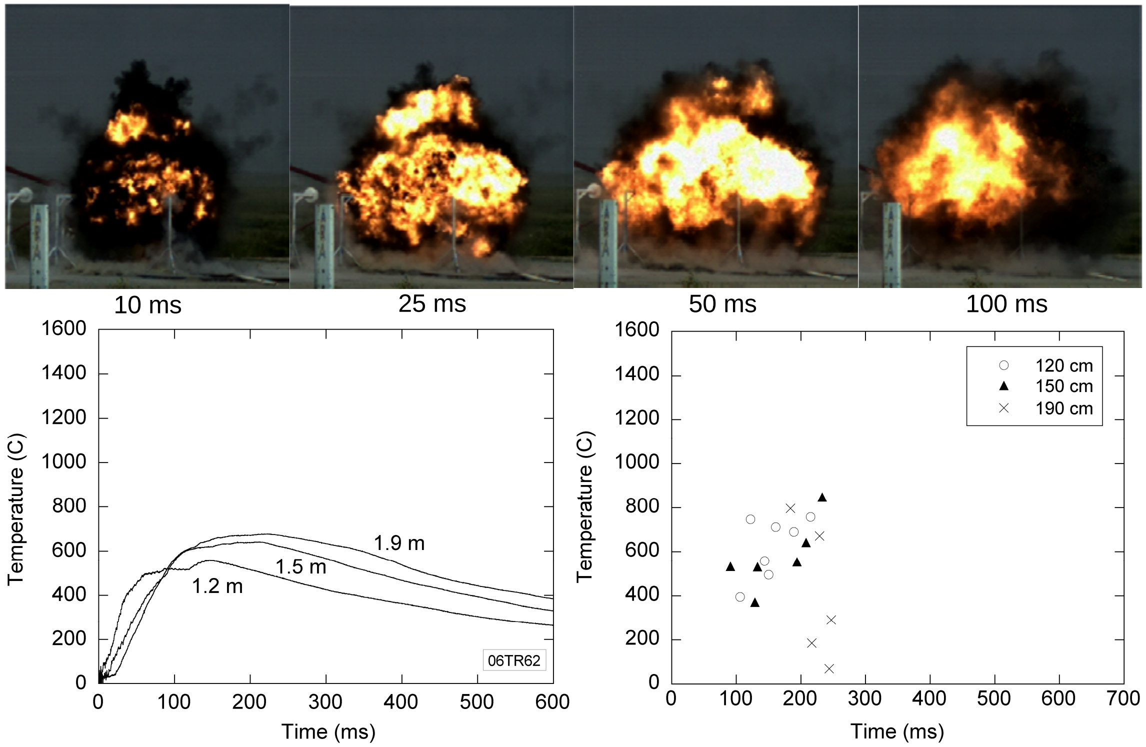

Figure 3. Photographs of detonation of 1 kg NM charge (top); example of thermocouple (127 µm) measurements at 3 locations (left) and peak thermocouple temperatures from multiple experiments (right).

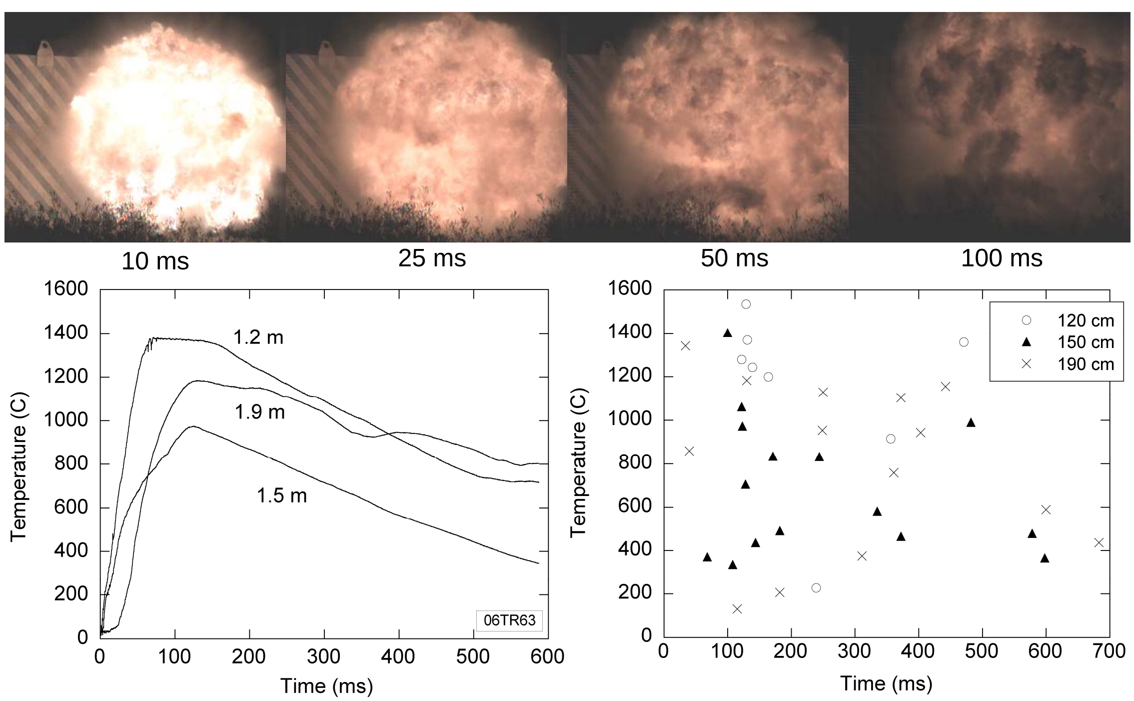

Figure 4. Photographs of detonation of 12.3 cm dia NM/Al charge (top); example of thermocouple (127 µm) measurements at 3 locations (left) and peak thermocouple temperatures from multiple experiments (right).