Spectroscopic study of radiation associated with hypervelocity impacts

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Abstract. In the two-stage light gas gun of the Shock Wave Research Center of Tohoku University, a spectroscopic study of hypervelocity impacts of cylindrical projectiles at an average velocity of 5 km/s on 2 mm thick aluminium bumpers has been carried out. The flash emitted from the jetting cloud during the impact process was acquired by a spectrometer and CCD camera. Attention was drawn on the CN violet bands resulting from the ablation of the polyethylene projectile. From the measured spectra, the average temperature of the jetting cloud was estimated to be around 8200 K in the case of head-on impacts on aluminium targets. Substantial atomic emission was also detected.

1 Introduction

The growing concern for the protection of space vehicles against space debris has initiated many studies around the world of the phenomena related to hypervelocity impacts. For many decades, researchers have studied the impact phenomenon with the ultimate goal of designing better shielding for spacecrafts orbiting the earth. The mechanism by which the impacting and target material undergo fracture and ablation is however not fully understood. Generally, it is agreed that upon impact, strong shock waves propagate both along the projectile and target. Simultaneously, rarefaction waves are created, satisfying the zero stress conditions at the free surfaces of the material involved (see Fig. 1) [1]. Fracture is believed to occur through a multiple-spalling process in which debris sizes are smaller with increasing velocity of the projectile. As the latter further penetrates the target, jets of fine particles are ejected from the sides at very high velocity, creating a radiating cloud in the surrounding gas. On the opposite side of the bumper, a debris cloud is formed consisting of fragments from both the projectile and target. This whole process has mostly been deduced from theoretical consideration and experimental investigations such as debris cloud visualization and crater analysis.

Studies in the past have shown that during the impact event, the fast jetting of debris from the front side is responsible for a brief flash, consisting of atomic and molecular emission [2]. This emission, if spectrally resolved, can give a lot of information about the nature of the impact (species created, correlation with velocity and angle of impact) and probably about the temperature reigning in this region.

Recently, temperature determination of hypervelocity impacts has been carried out by Sugita et al. [3] In these experiments, the emission lines of calcium were measured during impacts of quartz spherical projectiles on dolomite. Comparison of the experimental spectra with calculated ones yielded temperature estimations of these impacts. Similarly, in the Shock Wave Research Center, spectroscopic measurements in the near UV region of hypervelocity impacts of high-density polyethylene projectiles on thin aluminium bumper shields have been done with the idea of determining the temperature of the frontal jetting cloud. In this paper, the method used to analyze the spectroscopic data is discussed. The CN violet band has been chosen as candidate emitter because of its high emission intensity in the present experimental conditions and relatively straightforward numerical simulation.

2 Experiment

2.1 Setup

The experiments have been carried out in the two-stage light gas gun of the Shock Wave Research Center of Tohoku University [4]. Projectiles made of high-density polyethylene and weighing 4 g are fired at around 5 km/s on 2.2 mm thick aluminium targets (Al 2017). Impact tests on different target materials such as FML (Fiber Metal Laminate) have also been done and are presented elsewhere [5]. As shown in Fig. 2, the emission radiated briefly upon impact is captured by a condenser lens placed at an angle of 15° and is guided by an optical fiber into a spectroscopic system and CCD camera. The radiation is collected in a solid angle making a 10 cm circle on the region of impact. It is time-integrated, i.e. the recording of the CCD camera is triggered when the projectile cuts the laser beam situated in the free-flight section and stops about 30 μs after impact.

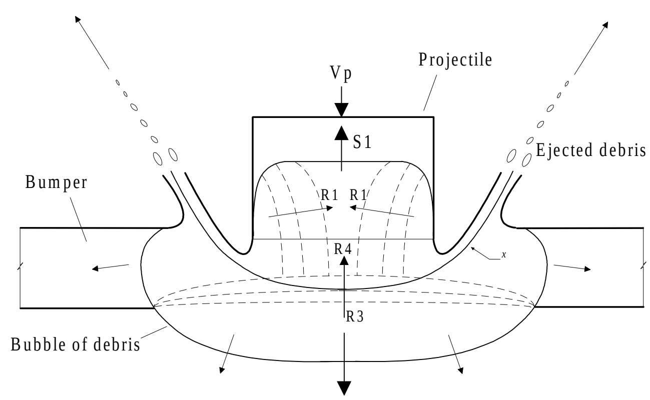

Fig. 1. Early stage of hypervelocity impact, after reflection of shock in target

2.2 Experimental conditions

Table 1 summarizes typical tests that have been carried out in the two-stage light gas gun facility. All the impacts were done for an average projectile velocity of 5 km/s in both normal and oblique angle impact configurations. The angles 51° and 64° were chosen based on a statistical study by Voinovich et al. [6] showing that for space vehicles in orbit around the earth, the probability of impacts with debris is highest at this range of angle. Two different test gases were used in the normal impact tests: dry air and N_2, at an average pressure of 600 Pa. Although different target materials have been tested, in this paper only impacts on aluminium bumpers are presented.

Table 1. Typical impact tests

Test	Gas	Velocity, km/s	Pressure, Pa
Normal	Air	5.06	600
Normal	N_2	5.23	600
Oblique 51°	Air	5.13	600
Oblique 64°	Air	5.20	600

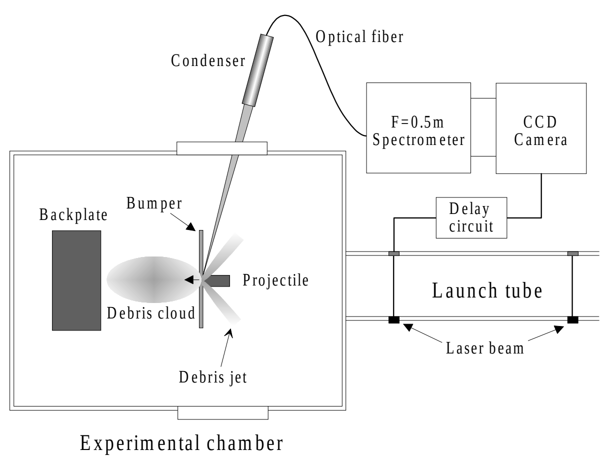

Fig. 2. Optical setup for emission spectroscopy

3 Results

3.1 Temperature determination

A commercial package, SPRADIAN by ISAS [7] is used to simulate the emission bands of the $\Delta v = 0$ band of CN, belonging to its $B^2\Sigma^+ \leftrightarrow X^2\Sigma^+$ electronic transition. It is expected that the temperature inferred from the CN spectrum will provide an estimate of the temperature around the impact point, in the surrounding jetting cloud. The following assumptions are made in the calculation of the spectrum and in its comparison to the experimental data:

- The impact is taken as an equilibrium process. Though this is certainly untrue, it simplifies greatly the calculation. Moreover, in the present case where temperature is determined from the time-integrated experimental radiation, it is expected that this value of temperature will be closer to the maximum attained in the gas near the impact region. Also, a single temperature is considered (the vibrational and rotational temperatures are assumed to be equal)
- Overlapping from other emission bands of N_2 and N_2^+ are ignored. This can be safely done since the contribution due to CN is very large compared to other species
- Line broadening due to pressure is taken into account in the calculation.

As depicted by Fig. 3, the relative intensities of the vibrational peaks of the $\Delta v = 0$ band of CN are very sensitive to temperature. The method of de-

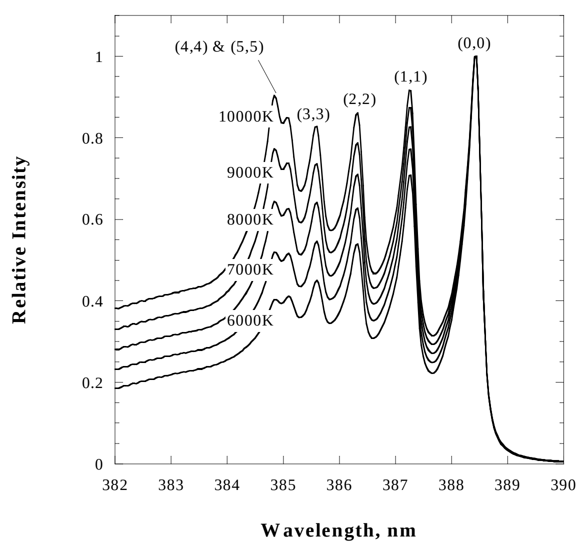

Fig. 3. Computed $\Delta v = 0$ band of CN at different temperatures

termination of the temperature from the measured spectra makes use of this characteristic by matching these peaks with values extracted from the calculated spectra. Only the first 4 vibrational levels are considered in this technique because the mutual overlapping of the higher levels makes the convergence of the calculation more difficult, and is superfluous.

3.2 Discussions

From the method explained above, the average temperatures of the different impact tests were determined and are summarized in Table 2.

Table 2. Calculated temperatures of the jetting cloud at different test conditions

Impact type	Gas	Temperature, K
Normal	Air	8300 ± 500
Normal	N_2	7700 ± 400
Oblique	Air	8200 ± 500

The average value of normal impacts of polyethylene projectiles on aluminium bumper in N_2 gas in the present experimental conditions is estimated to be

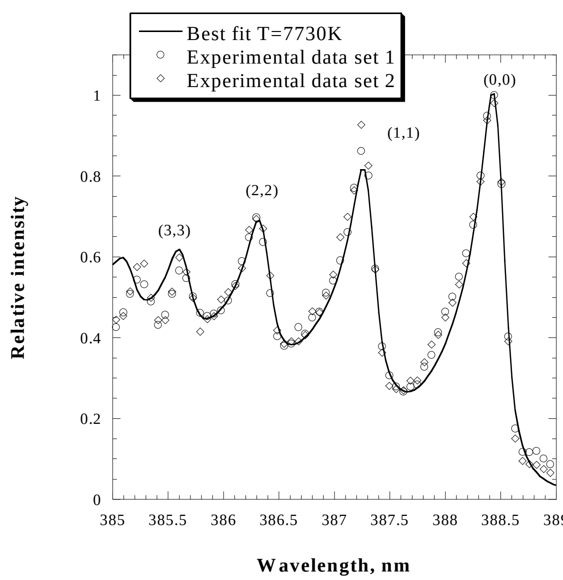

Fig. 4. Experimental and simulated spectra, normal impact, v=5 km/s in N_2

around 7700 K (see Figs. 4 and 5), lower than the same impact conditions in dry air, which is about 8300 K. This discrepancy is not clear since the mechanism of production of CN during these impacts is not fully understood. In general, it is reasonable to assume that during the impact event, CN is formed from exchange reactions of CH and N, themselves created from the dissociation of polyethylene $(CH_2)_n$ and N_2 respectively. In the case of dry air for instance, the presence of oxygen in the gaseous mixture may influence the reactions steps and in consequence, the impact temperature attained. Furthermore, the aluminium from the bumper will also readily react with the oxygen through a highly exothermic reaction, thus probably contributing to an overall raise in the temperature of the gas.

In the case of oblique impacts, only shots in dry air were executed. Since no clear distinction could be made from the two different angles tested, data from these two were analyzed together. The temperature determined from these series of oblique impacts in dry air is 8200 K and within experimental error, is of the same order as the normal impact case. So, the present calculated results do not show any difference between the normal and oblique impact cases. As stated earlier, the method used here tends to give the highest temperature attained during the impact process. Certainly, the in-depth differences between the normal and oblique impact processes cannot be captured by the present technique. A time-resolved analysis of the process by acquisition of time-resolved spectroscopy will therefore give valuable information on the formation of the jetting cloud in the different impact configurations.

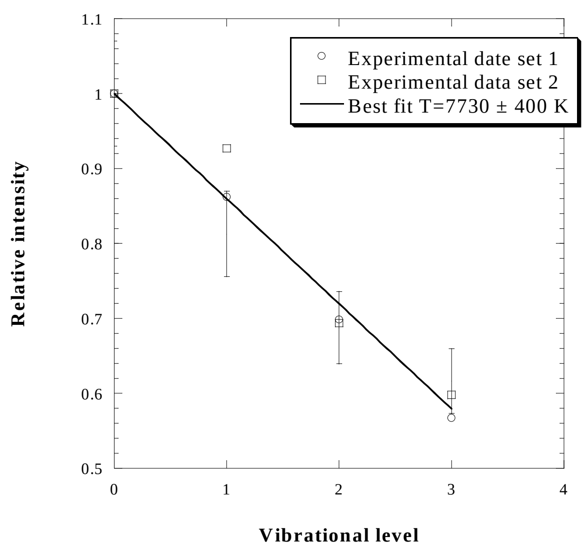

Fig. 5. Best fit of vibrational peaks at T=7730 K, normal impact, v=5 km/s in N_2

4 Conclusions

Spectroscopy of the radiation briefly emitted from the jetting cloud during the hypervelocity impacts of polyethylene projectiles on aluminium bumpers have successfully been carried out. The emission spectra of the CN violet band have been measured and their analysis by comparing to calculation has yielded average temperatures of the jetting cloud in different experimental conditions. Tests in N_2 gas gave the lowest temperature as compared to tests in dry air. No difference of temperature between normal and oblique impacts could be detected by the present method. Future work is in progress to analyze data from atomic lines. Further tests in which time-resolved spectroscopy experiments will be carried out are also under way.

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