FIREBALLS EJECTED FROM SOLIDS AND LIQUIDS BY LOCALIZED MICROWAVES

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ABSTRACT

This paper presents various aspects of our recent fireball studies and new experimental results of fireballs ejected from various solid and liquid substrates (e.g. copper, salty water, silicon, carbides). Our ongoing experimental analyses of these fireballs include measurements of small-angle X-ray scattering (SAXS) performed at the European Synchrotron Radiation Facility (ESRF), optical spectroscopy measurements, plasma diagnostics, and various ex-situ material analyses. The in-situ SAXS measurements reveal the fireballs' nano-structures, and further optical spectral analyses indicate the presence of the originating substrate elements in the floating fireballs (e.g. copper or sodium). Scanning electron microscopy of the dust debris accumulated on the chamber walls is used to verify the in-situ measurements of the dimensions and contents of the fireballs' nanoparticles. Our studies could be relevant to ball-lightning phenomena in nature and to a variety of practical technological applications conceived for these fireballs.

KEYWORDS: Fireball, ball-lightning, plasmoid, microwave plasma, nano-particles.

INTRODUCTION

The mechanism of fireball ejection to the atmosphere from molten hotspots induced in solid or liquid substrates by electrode localized microwaves was demonstrated recently[1)]. These fireballs float in the air, and can be sustained for minutes in the microwave field (typically ~1 kW at 2.45 GHz). A typical image of such fireball is shown in Fig. 1. Like previous laboratory-made fireballs[2)], they also demonstrate buoyancy and other features of natural ball lightning[3)]. Such fireballs are generated in our lab from various substrate materials, like silicon, germanium, ceramics, and even salt grains immersed in water[4)]. Optical spectral measurements revealed the dominance of the substrate materials in the light emitted from these fireballs, as for instance the strong sodium light at 589 nm emitted from a fireball generated from NaCl solution[4)]. Hence, it was proposed that this technique can be used to synthesize fireballs from various substrate components.

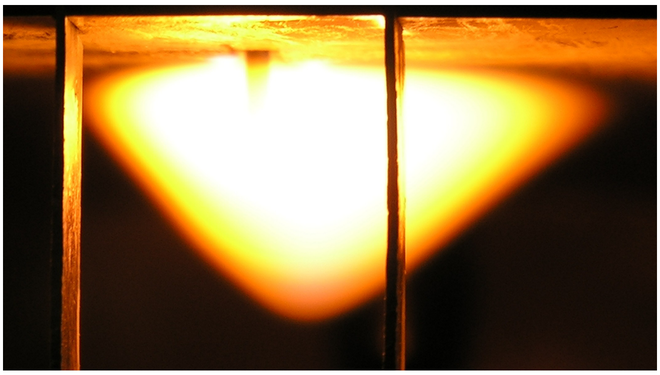

Figure 1: A typical image of a stable fireball excited in a microwave cavity[1)]

The small-angle X-ray scattering (SAXS) method was applied to study fireballs of this type using synchrotron radiation[5)]. The first fireballs studied by SAXS were made from borosilicate glass substrates, and their particle size distribution, density, and decay rate in atmospheric pressure were measured. The results showed that these fireballs contain particles with diameters of ~50 nm with average number densities in the order of $\sim 5\times10^{9}$ cm^{-3}. Hence, it was suggested that these fireballs can be considered as dusty plasma which consists of an ensemble of charged nanoparticles in the plasma volume. This finding was likened to the Ball-Lightning phenomenon explained by the formation of an oxidising particle network liberated by lightning striking to the ground[3)].

This paper presents our on-going studies extended to the recently discovered metallic fireballs made of copper or aluminum vapor, and to fireballs originated from liquids, like tap water or salt solution. Their experimental analyses are presented, including optical spectroscopy, SAXS, and scanning electron microscopy (SEM) results. This diagnostic ensemble reveals the fireballs' material content and particle size distribution.

EXPERIMENTAL SETUP

The experimental setup depicted in Fig. 2 consists of a WR340 rectangular waveguide terminated by metallic vanes under cutoff providing a direct view into the waveguide[1)]. The inner electrode enables the hotspot excitation intentionally hence stimulating the fireball in a controlled fashion. The microwave cavity is energized by a 2.45-GHz magnetron providing an input power adjustable in the range of 0-2 kW. Fireballs can be generated in this device from various substrate materials (e.g. silicon, glass, germanium, alumina, basalt) and forms (e.g. solids, grains, powders, liquids). This setup enables direct lines of sight to the fireball, as shown in Fig. 2, for viewing, image and video recording, optical spectroscopy, and X-ray scattering.

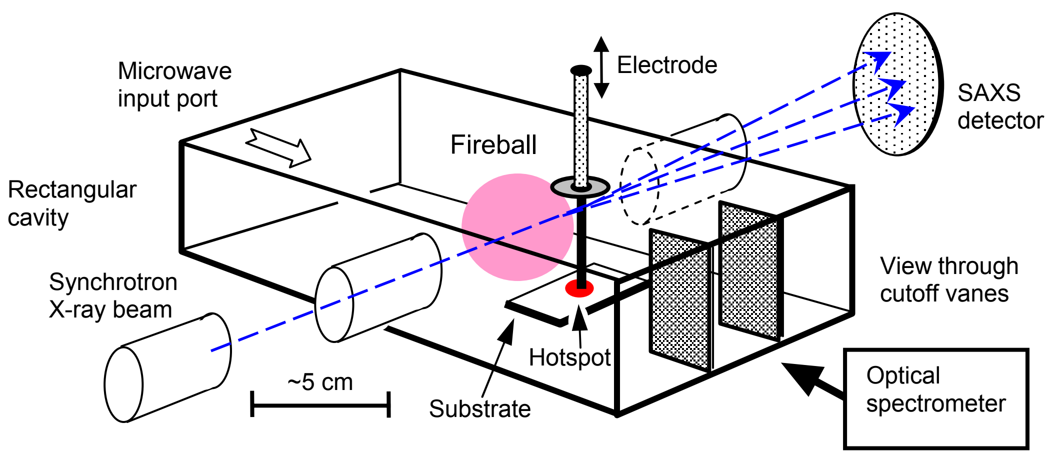

Figure 2: The experimental-setup scheme of the microwave-excited fireball.

EXPERIMENTAL RESULTS

The optical spectroscopy of the fireballs' emitted light shows clear spectral lines of the original substrate materials. For example, the fireball made of copper substrate and electrode (99.9% pure) produced emission lines associated mostly with copper. Figure 3 shows a typical spectrogram obtained by an AvaSpec 3648 spectrometer. The spectral lines of copper in the visible range, at 578 nm, 522 nm, 511 nm and 515 nm, and in the near UV range, at 327 nm and 325 nm, are clearly seen in this spectrogram indicating the dominance of the copper vapor in this fireball.

The Boltzmann plot method[6)] enables us to find the fireball's electron temperature, provided that local thermal equilibrium (LTE) is maintained. The LTE condition is evident for instance by the form of the OH radicals spectrum shown in Fig. 4a in a fireball excited from tap water, which agrees with a OH emission band form to be expected under LTE condition[7)]. Figure 4b shows for comparison the near UV spectrum of a copper fireball in air. The 327 nm and 325 nm copper lines are incorporated with the OH emission around 310 nm, which may indicate LTE also in the copper fireball (whereas the OH is provided by the air) as in the tap-water fireball shown in Fig. 4a. Similar results were obtained also with pure water as a substrate for the fireball.

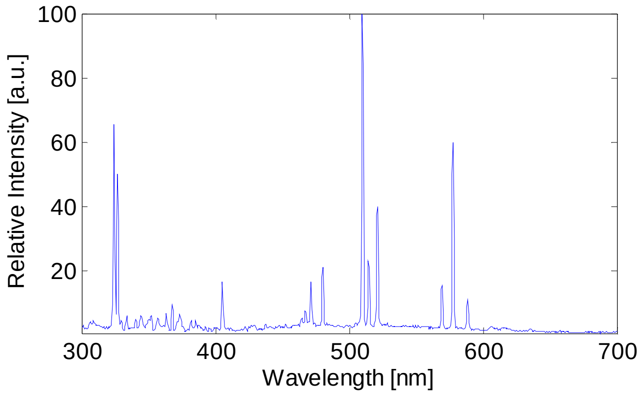

Figure 3. A typical spectrum of a copper fireball.

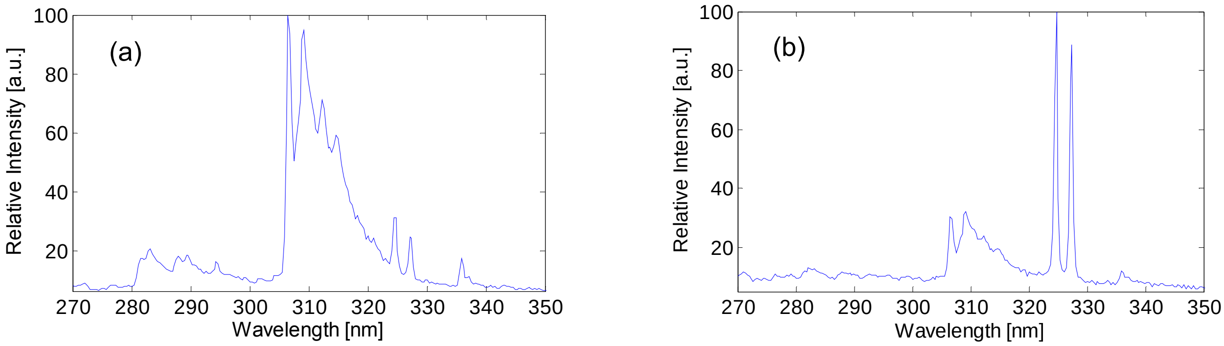

Figure 4. OH radical spectra of a tap-water fireball (a) and of a copper fireball (b).

A typical SAXS result measured at the European Synchrotron Radiation facility (ESRF) for a copper fireball is shown in Fig. 5a. By taking the inverse Fourier transform of the intensity versus Q curve[5)], one obtains the particle volume distribution as seen in Fig. 5a. This involves a numerical fitting procedure using the Irena Macros provided by the Advanced Photon Source (APS) SAXS beam-line. Three groups of particle size are seen here, around ~27 nm, ~65 nm and ~110 nm, which reflect the clustering together of individual primary particles.

The surface morphologies of the particles accumulated on the microwave cavity's ceiling were characterized *ex situ* using a Quanta 200 FEG Environmental Scanning Electron Microscope (ESEM) from FEI. Several zones containing particles with different morphologies were identified. Figure 5b shows typical *hedgehog*-like spheres with dimensions on the micrometer scale. The chemical composition of these spheres was found to consist mainly of Cu, with some impurities of Zn, Fe, O and Ca. Higher magnification images revealed that each *hedgehog* sphere is actually composed of much smaller particles on the scale of ~0.3 µm and smaller. This size match the right edge of the particle diameter distribution obtained by the synchrotron SAXS data (Fig. 5a). Similar particles are covering the whole surface between the spheres. It is likely that by using other analytical techniques with higher resolution and higher magnification, such as transmission electron microscopy (TEM), the size distribution will be shifted to lower values compared to that determined based on the ESEM image. It may be hypothesized that the spheres shown in Fig. 5b are agglomerates formed during cooling and deposition on the surface, and not inside the fireball itself.

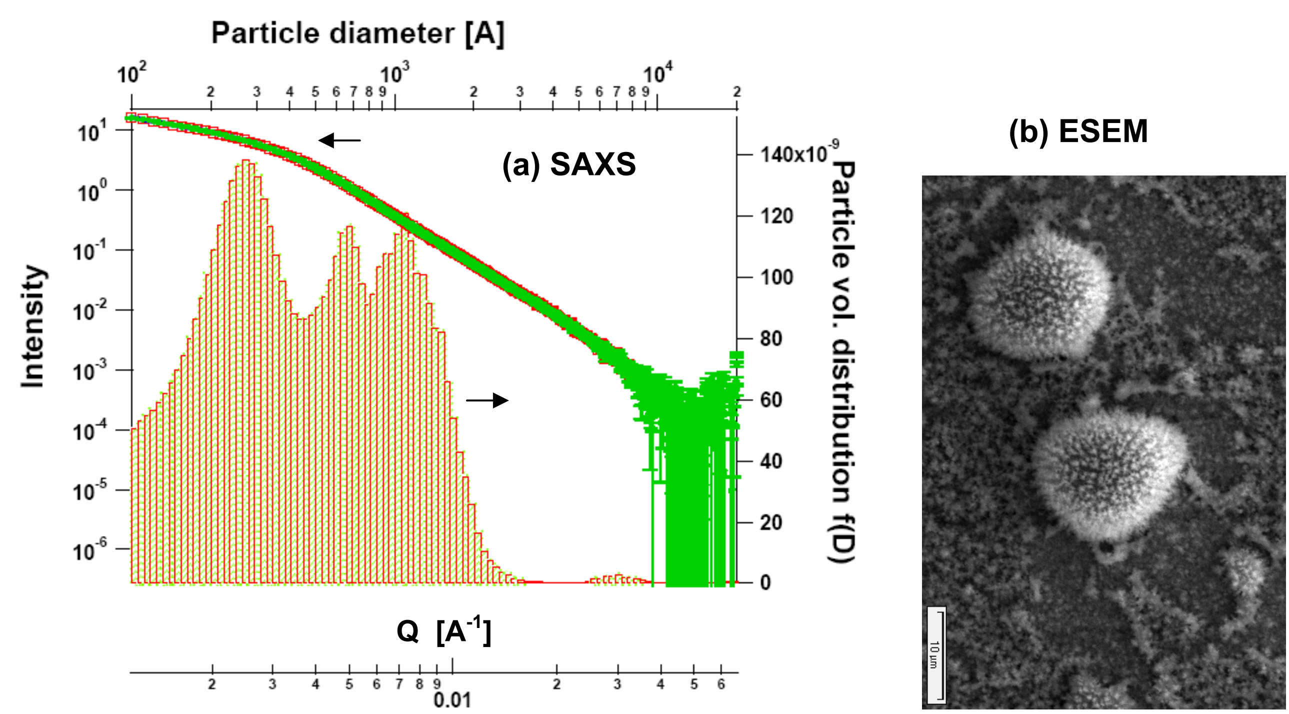

Figure 5. (a) Particle size distribution of a copper fireball obtained by X-ray scattering (SAXS). (b) *Hedgehog*-like copper clusters revealed by ex-situ environmental scanning electron microscopy (ESEM) on the microwave-cavity ceiling.

CONCLUSIONS

This study characterizes microwave-excited fireballs originating from various solids and liquids, including metals like copper. The optical spectroscopy shows that the fireball is made mostly of the substrate material (e.g. copper). The Boltzmann plot method[6)] assuming LTE leads to electron temperature estimates of $\sim 4\times10^3$ K for a 1-kW microwave input. Lower electron temperatures are observed at lower microwave input powers (from 3.3×10^3 to 3.8×10^3 K for effective microwave power from 0.2 to 0.5 kW, respectively). The fireball particles size distribution in the sub-micron scale is obtained by in-situ synchrotron SAXS measurements. Unique structures of the copper deposited by the fireball in *hedgehog*-like morphologies are revealed by ESEM imaging. This on-going study is aimed at the better understanding of the fireball phenomenon, and at the development of its synthesis methodology for various applications.

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