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Separating Hazardous Aerosols from Ambient Aerosols: Role of Fluorescence-Spectral Determination, Aerodynamic Deflector and Pulse Aerodynamic Localizer (PAL)

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Abstract

An aerosol deflection technique based on the single-shot UV-laser-induced fluorescence spectrum from a flowing particle is presented as a possible front-end bio-aerosol/hazardous-aerosol sensor/identifier. Cued by the fluorescence spectra, individual flowing bio-aerosol particles (1-10 μm in diameter) have been successfully deflected from a stream of ambient aerosols. The electronics needed to compare the fluorescence spectrum of a particular particle with that of a pre-determined fluorescence spectrum are presented in some detail. The deflected particles, with and without going through a funnel for pulse aerodynamic localization (PAL), were collected onto a substrate for further analyses. To demonstrate how hazardous materials can be deflected, $TbCl_3 \cdot 6H_2O$ (a simulant material for some chemical forms of Uranium Oxide) aerosol particles (2 μm in diameter) mixed with Arizona road dust was separated and deflected with our system.

Introduction

Environmental and occupational monitoring of hazardous aerosols, especially bio-terrorism threats by way of dispersal of pathogenic bio-aerosols, requires advanced systems that can classify air-borne particles in quasi real-time and *in-situ*. UV laser-induced fluorescence spectra (UV-LIF) are capable of, at least partially, distinguishing bio-aerosols from many kinds of ambient aerosols. It is this feature that makes UV-LIF a useful front-end or first-stage identifier that can classify individual particles (1-10 micron range) as bio- or non-bio- aerosols.

Unfortunately, some ambient aerosols, such as soot particles from diesel engine exhaust and cigarette smoke, have fluorescence spectra similar to bio-aerosols. In order to decrease false alarm rates, further specific analysis with a second-stage identifier, such as biochemical assay, Raman spectroscopy, FTIR, or mass spectroscopy, is required for the verification that the suspect bio-aerosols are threat particles, particularly for the determination of specific species of the bio-aerosols. All of these diagnostic/analytical

techniques will require several minutes to gather sufficient signal strength. Furthermore, the techniques will benefit from having the samples be mainly bio-aerosols, and not be burdened by the much larger concentration of non-bio-aerosols in the ambient. Therefore, the optically based UV-LIF system, is considered to be one of the fastest and best front-end systems capable of deflecting certain class of particles from the main particle flow column.

In this paper, a prototype of the front-end system is reported with details on the electronics that is keyed to having the UV-LIF spectra cue the particle deflector. Based on the dispersed UV-laser induced fluorescence (UV-LIF) spectra, selective deflection is achieved by separating bio-aerosols from an overwhelmingly large concentration of ambient aerosols. The deflection of the bio-aerosols is done aerodynamically rather than by electrostatic forces which require a charge/mass ratio be constant. The deflected bio-aerosols would have been spread out in a cone shaped distribution, but upon entering the funnel, they are focused onto an area of 1 mm in diameter. The deflector is cued in real-time depending upon the resemblance of the captured spectral data of a particle to a pre-defined spectral signature. Here, we use a 32-anode photomultiplier tube (32A-PMT) with its associated electronics to detect the single-shot laser induced fluorescence spectrum of each aerosol as it flows through the system. We present how an onboard digital processor can perform a particle discrimination algorithm on the captured spectral data.

Overview of the front-end system

The developed front-end system consists of the following key elements: (1) A concentrator that draws air at about 300 liters/min and is based on the virtual impactor principle. The concentrator keeps most of the particles in the 1 to 10 μm diameter toward a slower speed pump end that exit about 1 liter/min. (2) By using a specifically designed nozzle, the particles are forced to flow in a straight trajectory, localized within a cylindrical area of 600 μm in diameter for over a distance of at least 1 cm. (3) The exiting particles are aligned to flow through the intersecting volume (referred to as the *trigger volume*) of two diode laser beams with different wavelengths. Only if the particles travel through this intersection would the elastic scattered signal at two PMTs present and then issue an AND gate output. (4) This output serves as a trigger to the UV laser (263 nm, the 4^{th}-harmonic of YLF) which is synchronized to illuminate the detected particle from the trigger volume flying through the *sample volume* (defined as the intersection of the UV-laser beam and the focal point of the fluorescence collection lens). When this particle is irradiated with UV radiation (λ = 263 nm), the UV-LIF spectrum is dispersed by a compact spectrograph covering a wavelength span of 250 nm to 700 nm. This wavelength span of 450 nm is aligned with the detector elements from the 32A-PMT. (5) Every aerosol particle that transit through the trigger volume and subsequently transits though the sample volume is irradiated. The resulting fluorescence spectrum for each of these particles is captured and analyzed by the readout and processing electronics made by Vtech Engineering Corporation. (6) The on board processor determines whether or not a particle has the characteristic spectrum of known bio-threat aerosols. If a particle matches pre-determined signature criteria, the electronics trigger the air puffer to blast

out a puff of air, which then deflects that particular particle as it flows further down stream.

In the spirit of using several detectors, we present the role of a 32A-PMT with its associated electronics for detecting the single-shot UV-LIF spectrum of each aerosol on-the-fly. The multi-anode PMT is equivalent to having multiple separate PMT's, but in one unit. The uniqueness of the multi-anode PMT is in the electron multiplication section, which is discretely distributed throughout the housing unit. The objective of the multiplication section is to achieve 9-stages of electron multiplication (gain of nearly 10^6) while preserving the spatial integrity of a photoelectron that is emitted from a particular photocathode. It has the single-photon sensitivity, fast response (0.6 ns), and wide dynamic range (over 1000), but with enough spectral resolution for the broad band fluorescence spectra from bio-aerosol particles.

PhotoniQ-OEM: PMT Readout and Processing Electronics

Vtech Engineering Corporations' PhotoniQ-OEM readout and processing electronics system (PhotoniQ) combine several functions necessary for a multi-channel bio-aerosol detection instrument. As shown in the picture below, the electronics are actually composed of two boards. The smaller board (3" x 2.5") interfaces to the multi-channel detector, which in this case is the 32-APMT (H7260). The larger board (5" x 7") contains the analog processing electronics, the analog-to-digital converters, the input and output triggering circuitry, various instrument control I/O circuitry, and the digital signal processing (DSP) circuits. The two boards are connected with a shielded cable. A daughter-card (not shown) containing a high voltage power supply for biasing the PMT can be mounted to the larger board. The HV bias on this daughter-card is controlled by the DSP within the PhotoniQ. All of these electronics are powered from a single +5V, 9 Watt power supply.

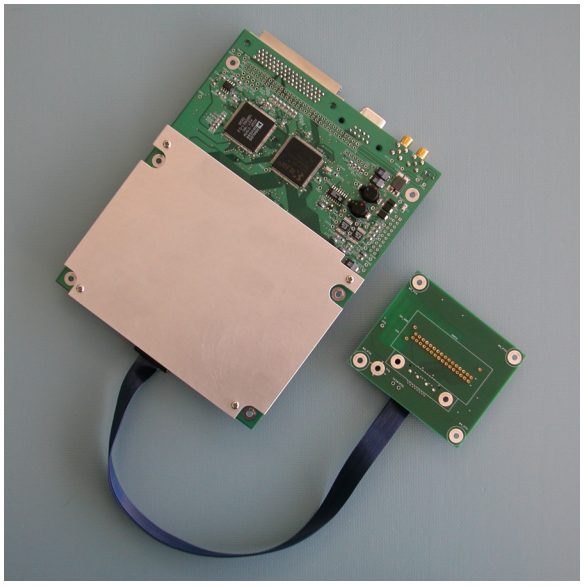

Figure 1: PhotoniQ-OEM readout and processing electronics system for multiple-channel detector (Vtech Engineering Corporations)

The PhotoniQ electronics receive an incoming digital trigger signal for each particle in the trigger volume. The internal triggering circuitry then adds a variable delay from that trigger that corresponds with the time necessary for the particle to travel to the sample volume. The trigger circuitry initiates a corresponding boxcar integration cycle to collect the fluorescence spectral signal while the particle is within the sample volume. The PhotoniQ can also generate the LED or LD drive trigger to be synchronized with these internal operations.

The 32 integrated signals are then further processed in the analog domain before being digitized by onboard analog-to-digital converters (ADCs). This resulting digital "vector" sample represents the particle's spectral information. The vector is then further processed digitally by the DSP. Finally, a spectral match algorithm is performed within the PhotoniQ's DSP to determine if the particle matches a stored particle signature and therefore should be discriminated. If the particle meets the algorithm's criteria, a digital signal is output from the PhotoniQ to actuate the puffer. Because of the re-programmable nature of the DSP, many different algorithmic detection methods can be supported using the same hardware.

The PhotoniQ also contains a number of programmable analog and digital input/output lines for general instrument control. These ADCs, DACs, and digital I/O can be used to monitor and control instrument biases, optical intensity levels, fans, motors, temperature, humidity, etc. All of these features are controlled from the onboard DSP.

The PhotoniQ operates as a stand-alone readout and processing system with the 32A-PMT, however during development the digital vector samples from each particle can be output to a PC using a high speed parallel interface. In this mode of operation, the data from particles that match the signature criteria are marked in the log file for continued analysis and algorithm verification. In addition to data logging, a LabView interface allows the user to control the various operational parameters of the PhotoniQ such as trigger settings, integration times, and particle algorithm/discrimination settings.

Actual Applications: Aerodynamic sorting and pulse aerodynamic localization (PAL) of bio-aerosols and/or hazardous particles cued on the UV-LIF spectroscopy

As we mentioned above, the UV-LIF system has been considered to be one of the best front-end for the bio-aerosol discriminator. When the concentration ratio of non-bio-aerosols to bio-aerosols is too high, more specific analysis is adversely affected. A technique for enrichment or sorting of bio-aerosols would then be essential. In order to get high speed and sensitivity, it is necessary for the sorted bio-aerosols to be localized into a small area to match the requirement of the second stage identifier.

Therefore, our front-end system can deflect, localize, and thereby enrich bio-aerosols which are selected by real-time detection and spectral analysis of single-shot UV-LIF of single flowing aerosols. Once an aerosol is found to have a characteristic

suspect fluorescence spectrum, a trigger signal is generated and sent to a pulsed valve to produce a fast directional puff of gas that deflects this particular bio-aerosol to a collection area. The particles are then localized by PAL onto a small area of a collecting substrate within a spot around 1 mm for the high density and small localization requirement for further second stage identification.

The puffer or the deflector consists of an electromagnetic actuated pulsed valve. It can generate a short (60 μs) supersonic air-packet (18 psi) within 20 μs, which only causes a very short interruption of the main aerosol stream and therefore deflects only very few neighboring "unwanted" particles along with the sorted particle. The puffer can selectively deflect either of two neighboring particles only 500 μm apart.

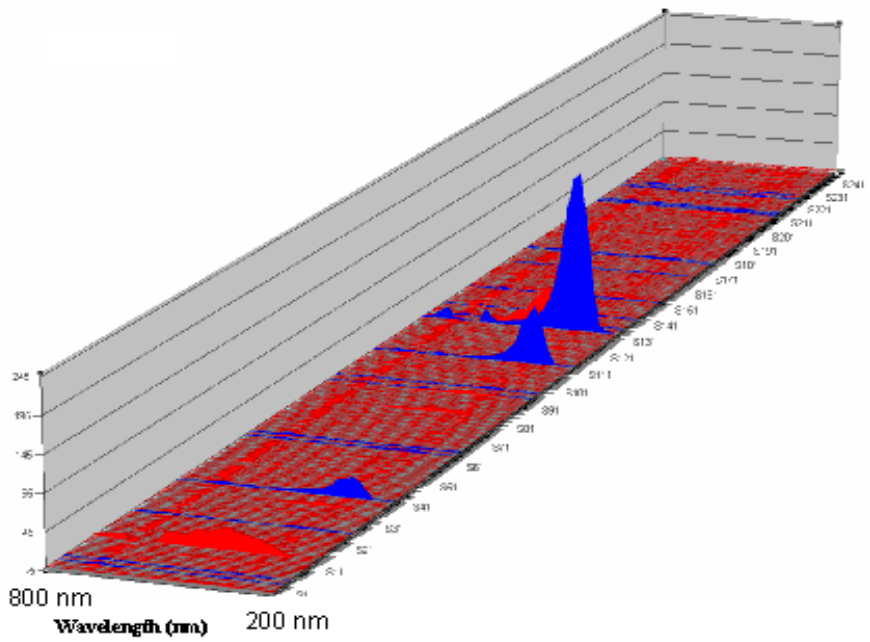

Figure 2: 250 successive single-shot fluorescence spectra from ambient aerosols (NRL on Aug. 18, 2004) illuminated by the 263 nm Q-switched Nd:YLF laser (50 μJ/pulse). The blue spectra are the detected ambient aerosol particles having bio-threat-like fluorescence spectra, while the red spectra are from non-bio-threat-like particles.

Figure 2 shows 250 successive fluorescence spectra from ambient aerosols (NRL on Aug.18, 2004) illuminated by the 263 nm Q-switched Nd:YLF laser (50 μJ/pulse). Among them, 19 particles have been assigned to be bio-threat-like aerosols and got deflected (the blue spectra), all of them have a strong fluorescence peak around 330 nm. And the other 231 particles with their corresponding fluorescence spectra did not meet the criteria conditions and have been considered as nonsuspect aerosols (the red spectra) without deflection. The corresponding collections of the deflected aerosols with different criteria definitions of fluorescence spectra are under analysis by FTIR spectroscopy.

The sorting of Bacillus subtilis from Arizona road dust (ARD) has been reported [1]. In this paper we will discuss the selective deflection of the fluorescent particles

$TbCl_3 \cdot 6H_2O$ in the midst of a high concentration of Arizona road dust. $TbCl_3 \cdot 6H_2O$ is considered to be a simulant material for uranium oxide (UO_x), a hazardous material. $TbCl_3 \cdot 6H_2O$ was selected because of its distinguished time-resolved fluorescence spectra, safe aerosol generation and ease of handling compared with UO_x.

In order to demonstrate the concept of our system, a mixture of $TbCl_3 \cdot 6H_2O$ and Arizona road dust (ARD) particles (equal spherical volumes ~2±0.3 μm in diameter) were used in laboratory tests. We combined the outputs of two ink-jet aerosol generators (IJAG) to produce the $TbCl_3 \cdot 6H_2O$ particles as the target aerosol in a minority concentration (20%) of the mixture, and ARD as the background aerosol (80% of mixture). Figure 3 shows the sorting results of $TbCl_3 \cdot 6H_2O$. The deflected and un-deflected aerosols are collected on separate SEM tapes held by microscope glass covers. The un-deflected aerosols are collected about 1 cm beneath the tip of the inlet nozzle. Images (the upper part of Fig. 3) taken by a digital camera show the overall dimensions of the deposited aerosols. The un-deflected aerosols (mostly ARD) are localized within an area smaller than 1 mm in diameter. However, the deflected $TbCl_3 \cdot 6H_2O$ aerosols are initially spread out over a large area because the puff of air is highly turbulent. Then the deflected particles are localized by a funnel into a small area around 1 mm in diameter. The details of the funnel along with computational fluid dynamic results will be discussed in a forthcoming publication [2].

A fluorescence microscope and a color digital camera were used to check the composition of the deflected particles when illuminated by a UV light source and a weak background white light. Most of the un-deflected particles are ARD particles (no fluorescence) with a few $TbCl_3 \cdot 6H_2O$ particles (the left lower part of Fig. 3), while in the deflected spot of 1 mm the particles are very pure $TbCl_3 \cdot 6H_2O$ particles (the right lower part of Fig. 3). Only a few dust particles can be found in the deposited area of the deflected particles. By counting the $TbCl_3 \cdot 6H_2O$ and ARD particles in this area, we obtained a concentration ratio ($TbCl_3 \cdot 6H_2O$ to ARD particles) of at least 10^3 to 1. Note, before our selection process the concentration ratio of $TbCl_3 \cdot 6H_2O$ to ARD particles was 1 to 4. This enriching factor (the ratio of the concentration of the sorted particles to the concentration of the aerosol mixture before sorting) is larger than 10^3 in this test. The localization of the deflected particles and subsequent enrichment in a one millimeter spot size create an ideal sample for FTIR, Raman scattering, or other biochemical analyses. This aerodynamic sorting technique, cued by the fluorescence spectra, demonstrates a unique capability for selectivity and efficiency in sorting interesting particles from background aerosols. It appears that this technique is a viable front-end instrument for sorting out “wanted or suspect” aerosols from ambient or background aerosols.

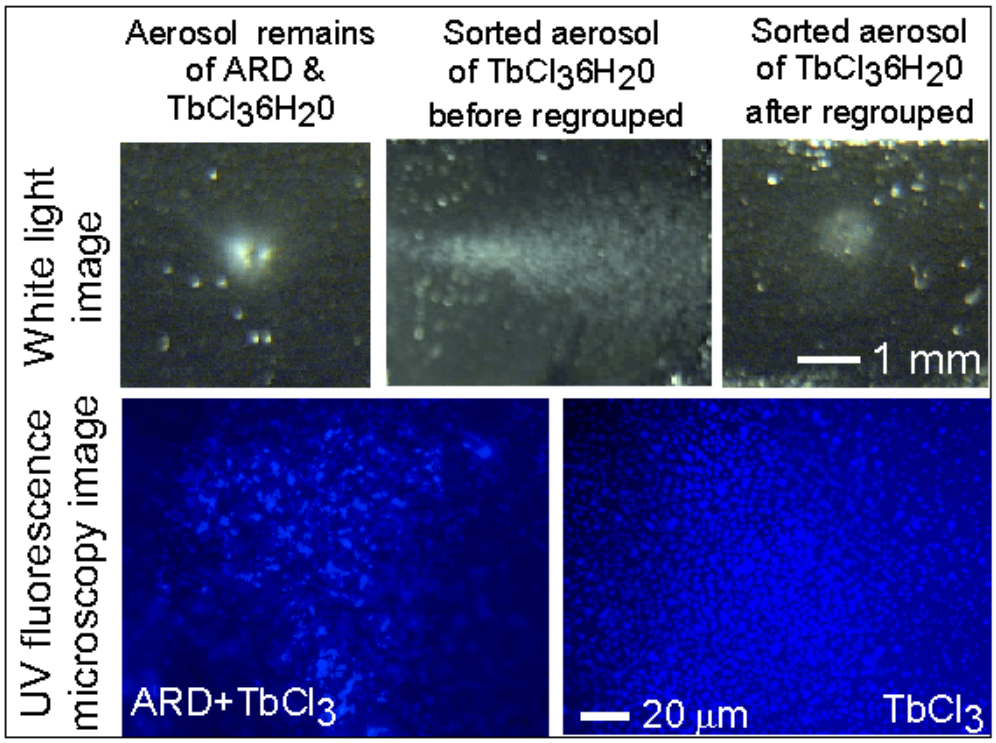

Figure 3: The images and microscopic fluorescence images of the un-deflected & deflected aerosol particles of $TbCl_3 \cdot 6H_2O$ and Arizona road dust (ARD).

Summary

A front-end system of real-time, in-situ bio-aerosol discriminator is reported here. It can deflect, localize, and thereby, enrich bio-aerosols selected by real-time detection and spectral analysis of single-shot UV-LIF spectrum of a particle on-the-fly. Once an aerosol is found to have a spectrum similar to that of a threat-like particle, a trigger signal is generated and sent to a pulsed valve. The valve then produces a fast directional puff of gas that deflects this particular bio-aerosol into a funnel that localizes the deflected particles onto a small area on the collecting substrate. Laboratory and field test results show that large enrichment factor of bio-species from the mixed aerosols or ambient aerosols can be achieved at least as high as 10^3. This technology will supply high concentration of suspect bio-aerosol particles for further specific analyses via bio-chemical assay technology or other subtle optical methods such as Raman spectroscopy.

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