Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-31028

FLOW VISUALIZATION TECHNIQUES FOR THE EVALUATION OF NON-CONTACT TRACE CONTRABAND DETECTORS

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ABSTRACT

Efforts are underway in the Surface and Microanalysis Science Division at the National Institute of Standards and Technology to study trace aerodynamic sampling of contraband materials (explosives or narcotics) in non-contact trace detection systems. Trace detection systems are designed to screen people, personal items, and cargo for particles that have contaminated surfaces. In a typical implementation of people screening, a human subject walks into a confined space where they are interrogated by a series of pulsed air jets and are screened for contraband materials by a chemical analyzer. The screening process requires particle and vapor removal, transport, collection, desorption, and detection. Aerodynamic sampling is the critical front-end process for effective detection. In this paper, a number of visualization techniques are employed to study non-contact aerodynamic sampling in detail. Particle lift-off and removal is visualized using high-speed videography, transport of air and particles by laser light scattering, and desorption surface heating and cooling patterns by infrared thermography. These tools are used to identify sampling inefficiencies and may be used to study next-generation screening approaches for aerodynamic sampling of particles and vapors.

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1. INTRODUCTION

The National Institute of Standards and Technology's Surface and Microanalysis Science Division, along with the Office of Law Enforcement Standards are working with the Transportation Security Laboratory of the U.S. Department of Homeland Security to provide tools for the fundamental metrology of trace explosives and narcotics detection. More specifically, these efforts concentrate on providing standardized testing methods and materials for trace detectors, improving current security screening technology, and developing next-generation screening technology [1-5]. In this work, we focus on the critical front-end process of sampling material from surfaces, including the processes of particle removal, transport, and collection prior to chemical analysis. Most available work in trace screening is centered on the chemical detection of materials rather than on the process of sample collection. Efforts are dedicated to improving the detection limits and specificity of ion mobility spectrometry, mass spectrometry, gas chromatography, and liquid chromatography. However, poor sample collection precludes detection by even the most sophisticated chemical analyzer. Here, we address the issues outlined by Settles [6,7] and the National Research Council [8] who point out the discrepancy between knowledge of environmental particle sampling and the fast, trace-level aerodynamic sampling of particles from specifically targeted surfaces required in trace detectors. Moore [9] specifically calls for more research in this little-studied application of aerosol science. This is an especially salient issue today considering that requirements for 100 % air and sea cargo screening must be met by 2010 [10]. Note that the techniques presented here are directly applicable to cargo, carry-on luggage, people, and parcel-package aerodynamic sampling for trace residues.

2. APPROACHES TO TRACE SAMPLING AND DETECTION

Working with bulk contraband materials (*i.e.*, creating improvised explosive devices or packaging narcotics) will inevitably contaminate the body, clothing, and surrounding surfaces with micrometer-sized particles of the contraband material. This is analogous to Locard's exchange principle in forensic science in which a subject and its environment exchange trace material [11]. During security screening, we attempt to collect and interrogate a representative sample of a person's or item's local environment and detect the contraband if it is present. The low volatility of many explosives and narcotics all but precludes detection of emanating molecular vapors [12] and so our primary focus is on collecting particles. Swipe sampling and aerodynamic sampling are two common approaches to collecting particles for analysis in a trace detector.

In swiping, particles are collected by drawing a swab of cloth across a suspect surface. The total area that can be swiped is limited by the surface area of the swab used and by the total time allotted for screening at a checkpoint. Furthermore, direct physical contact between a human security screener and a human subject may invoke privacy issues, thus only carry-on luggage, such as a bag or laptop, is swiped at airport security checkpoints. For a review of issues in swipe sampling of explosives see Verkouteren *et al.* [13].

Aerodynamic trace detection technologies are employed to overcome the limitations of swipe sampling, providing full-body, high-throughput, non-intrusive screening for trace contraband. In these systems, turbulent air jets are directed at an article to remove particles from the surface. The particle-laden air is transported by these air puffs or other air moving devices to a collection surface, usually a woven steel mesh, where particles are filtered from the air. The filter (or swab in swipe-based collection) is then heated in excess of 200 °C, near or above the sublimation temperature of many common explosives and narcotics. This produces a sample which is analyzed by a chemical detector, typically an ion mobility spectrometer or mass spectrometer.

Each step in aerodynamic sampling causes particle losses to the environment, meaning only a fractional mass of the original particles is available for analysis. To optimize the overall effectiveness of a detection system it is necessary to understand the dynamics of each underlying process and avoid using the chemical detector response as the sole performance metric. While the detector response is important, it provides less insight into sampling losses than a detailed study of particle removal, transport, and collection. The objective of our work is to compile and apply a series of unique measurement tools which visually examine the issues in aerodynamic sampling systems and to identify areas for improvement. Ideally, these tools should provide a quantitative measure of the efficiencies of particle removal, transport, collection, and vaporization, or provide qualitative insight into each step.

3. PRACTICAL METROLOGY AND THE NEED TO VISUALIZE SAMPLING EVENTS

3.1 Particle Removal from Surfaces

The two major concerns in optimizing particle removal in an aerodynamic sampling system are: 1. whether air flows are directed at targeted locations on the subject, and 2. whether material is removed from these surfaces. For optimum particle removal, the jet impingement location must coincide with the locations on the subject or item that are most often contaminated by handling contraband. When the jets impinge, the air closest to the surface applies a shear force to the particle, offsetting the electrostatic, van der Waals, and hydrostatic forces of attraction, thus inducing particle motion [14]. Depending on their composition and location on a surface, particles exhibit different modes of inceptive motion at different suspension rates. Particles may roll, slide, lift-off and bounce along surfaces when suspended. If they are on a porous or rough surface, particles may be driven deep into voids or be removed with less effort. Soft large particles tend to deform more than hard small particles [15] and the surface itself may deform on the micro-scale (*e.g.,* vibrating fibers) and macro-scale (*e.g.,* flapping clothing). Clearly, many factors determine whether a particle is removed from a surface. It is our objective to study these individually.

Much insight into particle removal dynamics in the laboratory is drawn from atomic force microscopy where a single particle is attached to a cantilever and either repeatedly brought into contact with a surface or dragged along it [16]. The attractive and frictional forces between the two surfaces are measured by the cantilever deflection to determine a critical force necessary for particle removal by lift-off or sliding. This process is useful for modeling particle removal [17, 18] but does not address real world scenarios for screening since our interest is in removing particles by unsteady aerodynamic drag and lift forces, not slowly-applied regularly-varying forces which are either purely normal or tangent to smooth model surfaces.

A focus in trace sampling metrology is typically measuring particle removal rates from surfaces using a method such as automated microscopy by counting particles on surfaces before and after screening [13, 19, 20]. Microscopy provides three-dimensional, time-averaged mapping of particle loadings and measures how much material is removed from a particular location, for a variety of particle sizes and types and over a wide range of surfaces. At NIST, fluorescent polystyrene particles sized between 10 μm and 50 μm in geometric diameter are employed in sampling applications because they are similar in size to particles that may be found in explosive residues [21] and because it is difficult to distinguish real explosive particles from the surface background. Using model particles also reduces explosives or narcotics contamination of surfaces in the laboratory. Nearly any surface type can be used with automated microscopy as long as its topography does not obscure the light emitted by fluorescent particles. Analytical methods such as mass spectroscopy, gas chromatography, and liquid chromatography can also be employed to measure the mass of explosives removed from a surface [22, 23]. However, these allow neither spatially resolved measurements nor individual particle discrimination; rather these chemical methods require dissolving the explosives remaining on a surface into a solution that is analyzed. This washing process also increases the uncertainty of the measurements.

Atomic force microscopy, automated microscopy, and other chemical analysis techniques can measure particle removal rates and some critical forces for motion, but they cannot readily identify the underlying causes of particle removal. Metrology is reduced to a single measurement for particle removal efficiencies and a single separate idealized measurement of force between model particles and surfaces. None of the methods mentioned allow for visualization of air flows as they interact with each other and the surface, nor can any *in situ* measurements of particle resuspension be made.

In this work, the schlieren optical technique is employed to visualize air jets as they develop and impinge upon a surface. Macro-scale resolution schlieren systems may be employed to ensure that jets are directed appropriately, and high-speed videography can be incorporated with microscopy and schlieren to visualize individual particle motions and make *in situ* measurements of particle removal rates from real surfaces. This enables measurement of particle velocities at inceptive motion as well as the net force applied to a particle. Additionally, infrared thermography may be used to visualize the impingement zone of air jets, the region of highest shear stresses, as a quality control measure for directing air flows.

3.2 Schlieren Imaging

Schlieren imaging is an optical technique commonly used to visualize convective, supersonic flows, or flows of mixed gases [24]. Using schlieren it is possible to image gasses that have a refractive index different than that of ambient air, *i.e.*, a supersonic air jet, heated or cooled air, or helium or nitrogen mixing with air. In this single-mirror schlieren imaging system, a diverging light beam passes through the test area where refractive index gradients bend the light away from their coincident path. The light then fills a spherical mirror and returns to a beam splitter that steers the beam as it approaches its focal point. A razor blade is positioned exactly at the focal point of the beam where a fraction of the bent light is cut off, creating an image with light and dark contrasts representative of the density gradients in the test section. Excellent examples of schlieren imaging for homeland security applications can be found in Settles [6, 7]. Here we use a single-mirror coincident beam schlieren system, diagrammed in Figure 1, with a spherical mirror of 40.6 cm diameter with a focal length of 244 cm.

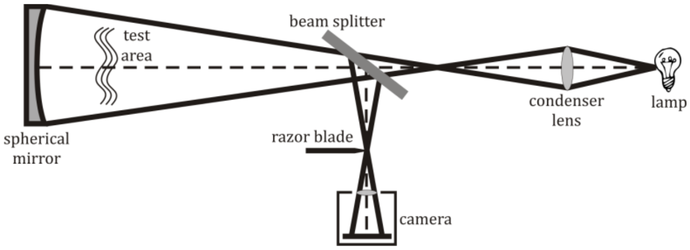

Figure 1. Single-mirror coincident schlieren optical setup. Adapted from [39].

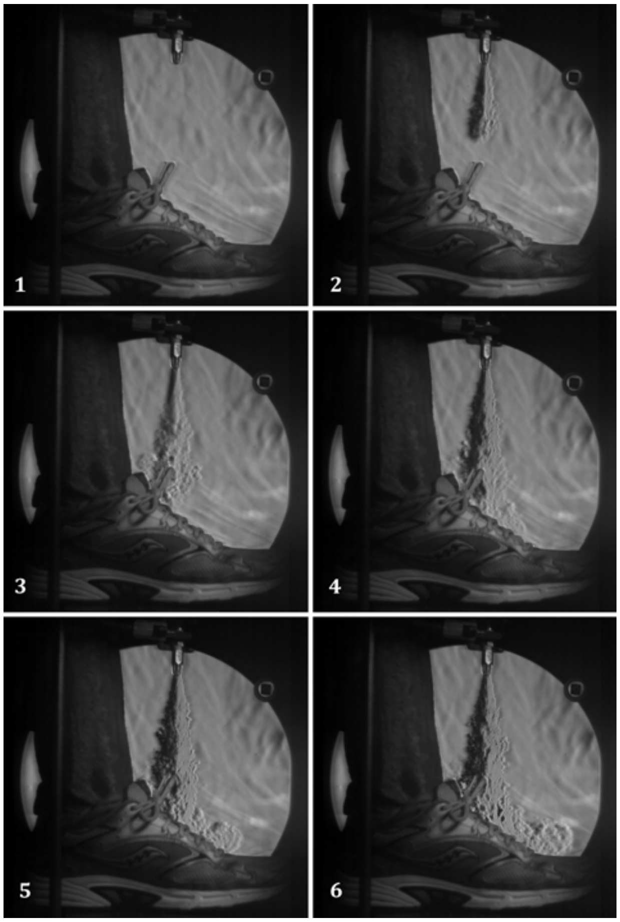

Figure 2. Images of jet impingement on a shoe using a schlieren optical system. Each image is 3 μs apart.

Figure 2 shows a sequence of images visualizing jet impingement on a shoe surface. Here, a round jet with a 5 mm nozzle diameter is used to visualize helium gas fired for 100 ms at a stagnation pressure of 620 kPa. It is possible to see the free jet, impingement region (the region of highest shear stresses), and the wall jet that forms along the surface of the shoe. Figure 3 shows a sequence of schlieren optical images from an air blade. An air blade (also called air knife) is used to produce a linear curtain of air that can cover large surface areas. Here, the air blade is 76 mm long with a 50 μm slit-opening. This schlieren technique is most useful on the bench-top as it requires a fixed focal plane and only visualizes the interactions between gases and the surface effect on the gas, but does not image surface features. A method of visualizing the suspending gas using schlieren on the micro-scale is currently under development and shows promise for measuring the velocity and turbulence level of impinging gas jets.

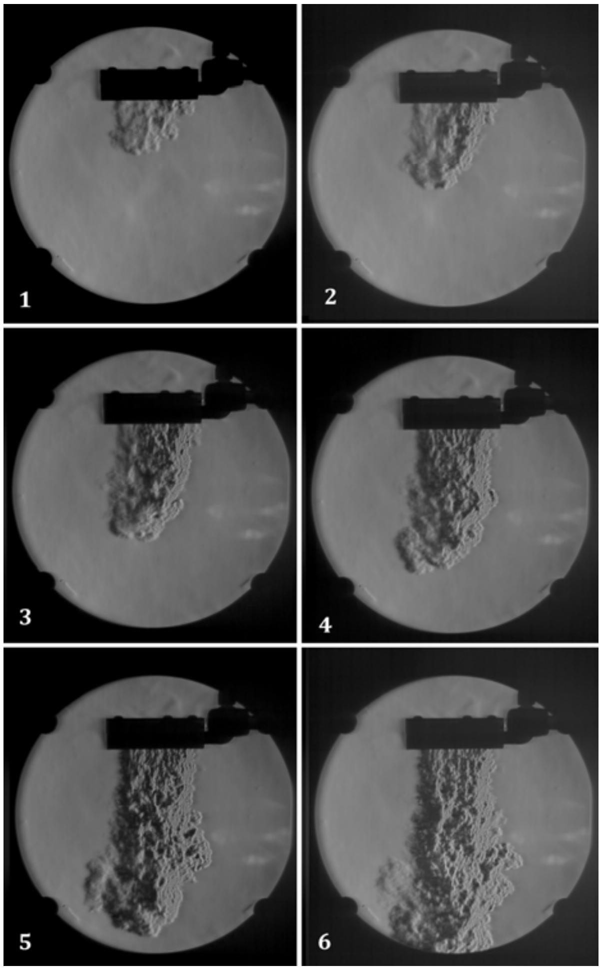

Figure 3. Schlieren images of an air blade being fired for a 100 ms pulse. Each image is 3 μs apart.

3.3 Infrared Thermography

Infrared thermography is useful for imaging surface effects of impinging jets, as shown in Figure 4. The human body is a heat engine, warmer than indoor air and clearly visible in the infrared wavelength range, even when insulated by clothing [25]. When jets impact, skin and clothing surfaces are convectively cooled revealing the impingement zone. We visualize these temperature differences with an infrared camera at 50 frames per second (FLIR Thermovision A40 infrared camera). Figure 4 shows two examples of infrared thermography being utilized for surface imaging. The impingement regions of both an air blade and an air jet are illustrated by the dark color zones. It is expected that the largest particle removal efficiencies are found at locations identified by these dark regions in Figure 4; the regions of highest heat transfer correspond to the regions of highest shear stress. Flow visualization by infrared thermography also aids in explaining the variability in particle removal depending upon source location on the surface.

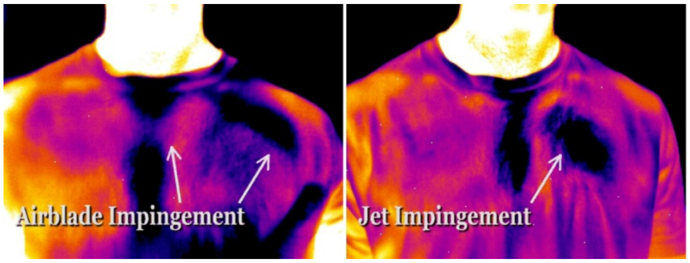

Figure 4. Images of air blade and air jet impingement on a subject in a sampling system by infrared thermography. The dark regions identify areas where jets are impinging on the subject.

3.4 High-Speed Videography

High-speed micro-videography is tremendously useful as a measurement tool to image particles as they are suspended from surfaces by air jets. Imaging suspended particles enables measurement of the time scale for particle suspension and particle velocities, accelerations, and initial trajectories. It is also possible to determine the modes of particle suspension such as rolling, sliding, or direct pull-off and determine how particles interact with each other and the surface, visualizing fracture of agglomerates, particle bounce, and particle and surface deformation.

In the system described here, images of particles resuspended from surfaces by air jets are taken at up to 250,000 frames per second with a Photron ultima APX-RS digital video camera on an Olympus BH-2 microscope using a 5x objective. Particles are difficult to track using fluorescent light sources because the light emitted by particles is insufficient for the short exposure times required in high-speed videography. Particles can be resolved spatially down to approximately 5 μm with this system. At higher magnifications, the spatial resolution of the system increases but limits the amount of light available for imaging.

High-speed videography coupled with microscopy provides spatially and temporally resolved images of particle lift-off events. The same removal rates that were previously measured after the fact may now be measured *in situ*. As an example, Figure 5 shows counts of a population of 20 μm polystyrene particles on a glass slide suspended by an air jet and imaged at 30,000 frames per second.

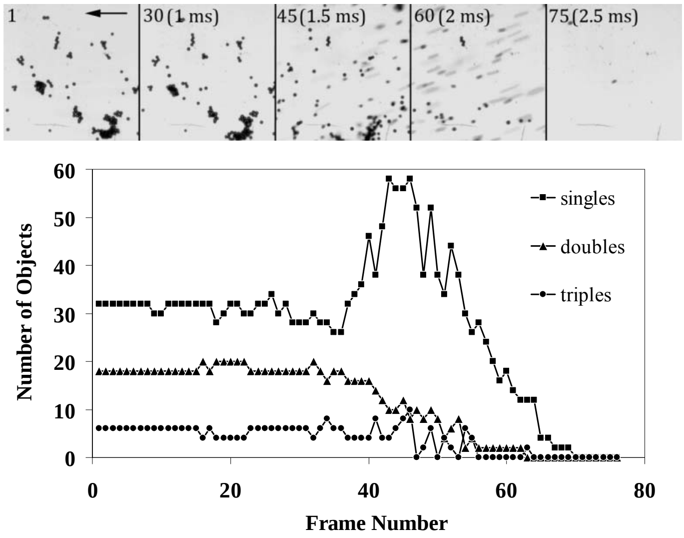

Figure 5. Polystyrene microspheres (20 µm) removed from a glass slide by an air jet impinging from right to left. Particle counts are presented for individual video frames.

It is possible to qualitatively and quantitatively visualize the breakup of agglomerates into single particles, and by using image processing codes, distinguish between single and multiple particle clusters. The plot in Figure 5 illustrates how high-speed videography coupled with microscopy and image processing can count particles as a function of time (or frame number). Here, a jet is fired from right to left at frame number 1. The plot shows that the number of singles, doubles, and triples in the field-of-view remains relatively constant until frame 40. At frame number 40 (time = 1.3 ms), particles outside of the field of view begin to bombard the stationary particles, indicated by the sudden increase in singles, liberating them from the surface and transporting them out of the field of view. By frame number 70 (time = 2.3 ms), all particles are removed. Data like these are important because they allow one to visualize the cascade of events that govern particle removal in real-time.

This technique can be extended to visualizing particles on cloth or other woven surfaces [20], an example of which is presented in Figure 6. Here, 20 µm fluorescent polystyrene microspheres are dry-transferred onto a woven cloth. An air jet at 100 kPa is pulsed for 100 ms and visualized at 36,000 frames per second. Overlaying the "before" and "after" images, along with image processing color channels, allows one to visualize particles that have moved or been liberated, as well as particles that remain on the cloth.

With this high-speed particle tracking technique, it is possible to establish which surface features contribute to or inhibit particle removal from irregular surfaces such as cloth. By examining the high-speed movie (which cannot be shown here) in Figure 6, the following are of note:

1. Particles are removed first from fibers extending from the surface.
2. Once removed from the surface, agglomerates of particles break into smaller groups and single particles.
3. Particles interact with the surface once they have been suspended, bouncing along it and suspending other particles in a cascade of removal events.
4. On the macro-scale, clothing displacement is too slow to have a primary effect on particle removal. All particles (approximately 300) are removed in 17 ms although the jet was fired for 100 ms and no fabric displacement occurred in this time frame.
5. Cloth flapping may have a secondary effect by introducing a fresh portion of a particle laden surface to high-shear air flow.

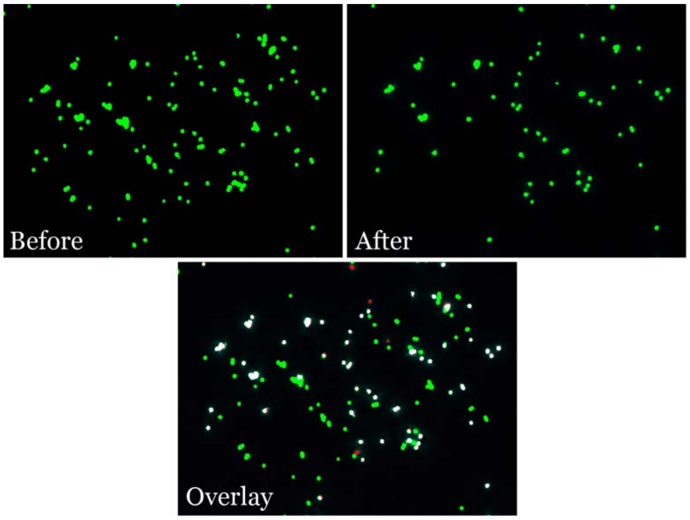

Figure 6. Fluorescent polystyrene microspheres (20 µm) on a woven cotton imaged before and after jet impingement. In the overlay image, particles that are green have been removed, particles that are white have remained on the cloth, and particles that are red have shifted position (either by sliding or rolling).

3.5 Particle Transport to a Collection Surface

Once particles are removed from the surface, particles must be transported through the air to a collection surface or volume, where the sample is concentrated before being sent to a chemical detector. High-velocity turbulent air flow is desirable for loosening particles from surfaces because it imparts a large shear stress onto a surface. Unfortunately, these same air flows hinder the transport of material to the collector by diluting particle concentrations in air and vectoring some material away from a collector. Ideally, the volume of air used by air jets should not exceed the amount of air that passes through the particle collector. Sometimes, more air is injected and entrained into the aerodynamic sampling system than is sampled through the collection filter. This ensures that only a portion of the liberated particles are transported to the collector. A flow rate mismatch such as this ejects particle-laden air from the test section. Particle transport efficiency is directly proportional to the fraction of particle-laden air that is sampled. When fewer particles are transported to the collector, detection rates may fall, thus increasing the potential for false negative alarms.

To measure particle transport rates independent of particle removal rates, particles collected on the filter are either imaged in place or washed off and re-filtered for particle counting by microscopy. Otherwise, particles are dissolved and analyzed by chemical methods. Note that these methods do not independently measure transport and collection rates. Another novel approach which measures transport rates independently from collection is aerodynamic particle counting. Light scattering, light extinction, or time-of-flight aerosol particle counters can be used to measure the number of particles at a particular location in a sampler. However, this is generally a point measurement since the sampling tube diameter is chosen to match the local air velocity and is quite small, on the order of millimeters. Aerodynamic particle sampling has its own limitations as a measurement method in that it cannot collect and discriminate between types of particles in all types of air flows and so particle background counts in a room may interfere with tracer particle counts. Sampling efficiency rates for aerodynamic particle counting generally rely on the particle size, velocity ratio between the ambient and collection air flows, sampling angle, particle charge, and sampling tube length [28]. These methods of measuring particle transport efficiency do not provide insight into the transport process. Specific causes of particle losses are not evident, and can only be identified after taking many measurements varying the types of particles and source location on the subject.

Real-time visualization of the air flows in a sampling system would allow designers to make informed changes to sampling routines to better convey particles to a collector. Large areas of flow within the sampler and into the ambient air of the surrounding room may be mapped during screening. Most importantly, specific causes of loss may be identified, *i.e.* jets overloading the collector inlet, air fans blowing material away from the collector inlet, or particles impacting on a surface and sticking. Laser light scattering is proposed as a means of imaging the air flows within aerodynamic sampling systems. It may also be used to image the flow of a particle source aerosolized from the body during screening. Without much change to experimental design, laser light scattering may be coupled with automated microscopy, chemical analysis, and aerosol particle counting, providing both a quantitative measure of particle transport and a means to explain losses.

3.6 Laser Light Scattering

Following the flow visualization method outlined by Craven and Settles [27], laser light scattering of droplets and particles is used to track air flows and particle plume distributions in and around non-contact sampling systems to determine which flow features contribute to particle losses. In this approach, a laser beam is directed at a cylindrical glass rod, which spreads the beam into a 2-dimensional sheet of laser light. Theatrical fog is introduced into the sheet and is illuminated only in the laser sheet, creating a cross-section of the flow field. Flow visualization takes less time and effort than a full computational simulation of the unsteady turbulent equations of fluid motion and provides the necessary velocity, turbulence intensity, and concentration information to make informed choices to improve aerodynamic transport of particles.

Particles removed from the subject can also be tracked by laser light scattering. The path of the particle plume simulates the path that contraband particles may take as they are removed from the body and transported by air flows. Figure 7 shows the particle plume as it spreads from a mannequin's chest to the inlet during screening in an aerodynamic sampling system that samples near the feet. A jet of air, vectored downward, impinges onto the mannequin near the neck. Here the mannequin is viewed from the chest to just above the knees. The laser light sheet bisects the chest vertically. In each frame, the spread of talc powder is clearly visible as it is transported downward along the torso.

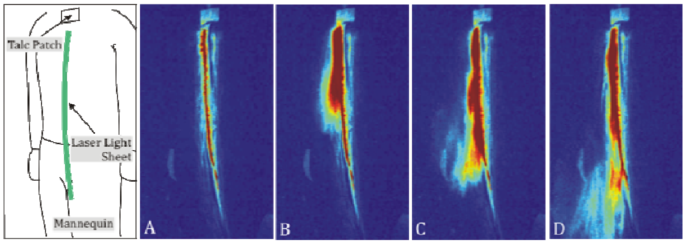

Figure 7. Spread of talc particles from the chest down along the body to the collector. Frames are 33 ms apart.

By comparing particle plume geometry and pixel intensity from flow visualization images with aerodynamic particle counting data taken simultaneously, an estimate of particle transport efficiency may be made. Although inert particles are used here, particles with known quantities of trace analyte incorporated in them may also be used and the detector response noted as a third measure of particle transport effectiveness. Together with the basic aerosol measurement theory outlined by Baron and Willeke [28], assumptions for each measurement method may be tested and the effects of decoupling removal, transport, collection, and detection efficiencies understood.

4. CONCLUSIONS AND FUTURE WORK

Several measurement tools and techniques are available to characterize each step of aerodynamic sampling including particle removal, transport, collection, and desorption. Fluid and heat flow visualization as well as high speed videography aid in understanding the underlying physics of sampling trace contraband in these non-contact systems. A solution to increasing sampling efficiencies must take into account all sampling processes as well as the screening throughput, cost, space, and maintenance issues in a field-deployable system.

The lessons learned from studying current aerodynamic sampling technology can be applied in three ways: to improve existing technology with minor changes, generating new sampling designs and technology, and to determine the necessary standard materials and practices for testing and evaluating system performance. These lessons may be applied for a range of trace sampling applications, including screening vehicles, people, luggage, and air and sea cargo containers. The effectiveness of aerodynamic particle sampling depends on the properties of the targeted particles and surfaces. What has been learned for sampling trace contraband and other model particles in general may be useful in other homeland security screening applications including chemical, biological, radiological, and nuclear detection methods.

5. ACKNOWLEDGEMENT

The Science and Technology Directorate of the U.S. Department of Homeland Security sponsored the production of this work under an Interagency Agreement with the National Institute of Standards and Technology.

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