The Development of an Aerodynamic Shoe Sampling System

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***Abstract*— In collaboration with the Transportation Security Laboratory, the National Institute of Standards and Technology has been developing a prototype shoe sampling system that relies on aerodynamic sampling for liberating, transporting, and collecting explosive contamination. Here, we focus on the measurement science of aerodynamic sampling with the goal of uncovering the underlying physics of the flow fields within these sampling systems. This paper will cover the results of a series of experiments that were used to help with the design of our prototype shoe sampling system. Laser light-sheet flow visualization revealed the bulk fluid motion inside and around the sampling system. Polymer microsphere particle standards were used to quantify the particle release efficiency of the shoe sampling system. Patches containing a known mass of explosives were also used to determine the effectiveness of particle release in the shoe sampler. Results from these experiments indicate that particle removal efficiency at a specific location is strongly influenced by its distance from an air jet and the type of explosive or material on the surface. The successful application of these flow visualization techniques and other metrology tools has helped us construct the sampling portion of a shoe screening prototype. The hope is that these tools will be useful to others who are developing next-generation aerodynamic sampling technologies.**

This paper contains embedded multimedia in the form of video sequences. The graphics with figure captions that are labeled "Video" should begin to play when you click on the image. You must have Adobe Acrobat Reader 6.0 or later to view these videos. All videos are imaged at 250 frames per second with a high-speed digital camera.

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I. Introduction

Aerodynamic sampling of people, cargo, and other objects is an emerging methodology for high-throughput, non-contact trace explosives screening at security checkpoints. Non-contact sampling provides an objective analysis without the need for physical contact, and offers high-throughput which can reduce congestion in high-traffic areas. The technology is based on fundamental principles from fluid mechanics, gas dynamics, and thermodynamics and when implemented properly, can be used to efficiently transport an explosive sample from a surface to a collector.

Of particular concern is explosives concealment in shoes, which has lead to the requirement for all airline passengers to have their shoes removed and screened. Sampling shoes without the need to remove them could potentially lead to significant improvements in screening throughput time and passenger compliance. The goals of this project were to investigate next-generation techniques for sampling shoes and determine the best approach for removing and transporting trace explosive residues from shoe surfaces to a collection device. The prototype shoe screening device designed during this project was based solely on the aerodynamic characterization of air jet and airblade impingement on shoe surfaces and the consequent removal and transport of microscopic particles.

Here, we focus on the measurement science of aerodynamic sampling with the goal of uncovering the underlying physics of the flow fields within these sampling systems. Scientists at NIST have been using fluid flow visualization techniques to study the role of fluid mechanics in trace explosives detection. These methods of flow visualization have been available for decades [1], but only recently have they been applied to Homeland Security-related topics [2].

This paper will outline the development of the shoe sampling system and focus on the techniques used to evaluate the performance of the system at two different design phases.

Lessons learned from the Phase 1 prototype provided useful insight into the shortfalls of the original design and ultimately led to significant improvements in the Phase 2 prototype.

II. PHASE I PROTOTYPE

A. *Shoe Sampler Construction and Description*

Components of the Phase 1 prototype include an air mover (blower), a converging inlet duct, two air jets, and one air blade. The air mover is a 1.5 KW, 240VAC, 3 phase centrifugal blower and is regulated by an AC motor controller. The air jets and blade were purchased from Exair.com (models 1102 and 110003). An image of the Phase 1 prototype is shown in Fig. 1.

Air jets have been the primary method for removing particles in non-contact aerodynamic sampling systems such as trace detection portals. In current portal implementations, the flow rate of the main air mover is set to a constant flow rate. When the jets fire, a large influx of additional air is added to the system that results in a fraction of the air "spilling" out of the portal chamber. This spillage issue, also referred to as an "impedance mismatch", can potentially be remedied by matching the blower flow rate with that of the jets and air blades. In previous unpublished work, several commercially-available jets and air blades were evaluated to determine their flow rates and jet patterns. Our conclusions from this work indicated that air blades, while offering several advantages in particle removal from surfaces, should not be the only type of jet used while designing next-generation prototype sampling systems. Traditional air jets offer the benefit of high velocity, and subsequently the benefit of large aerodynamic shear forces, but often introduce excess mass flow into the system. A trade-off between velocity and flow rate must be considered when planning stand-off sampling systems that are limited to a set flow rate intake.

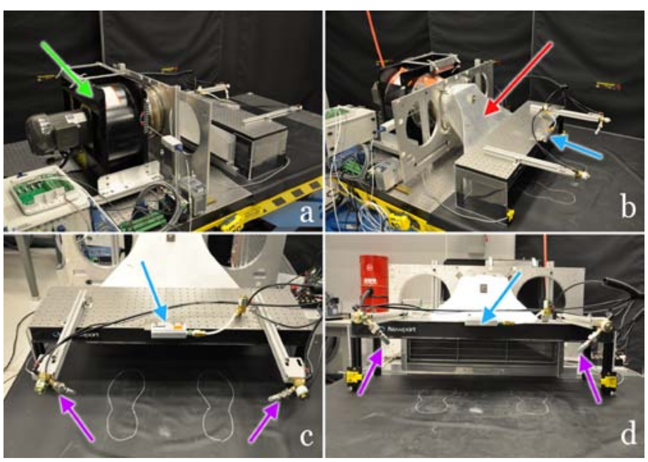

Figure 1. Collage of the Phase 1 prototype shoe sampler. The green arrow in (a) shows the main blower unit while the red arrow in (b) shows the converging inlet duct. A single 7.6 cm air blade is shown with a blue arrow and two air jets are highlighted with purple arrows.

A critical element in any aerodynamic sampling design is knowledge of the flow rate of the blower compared to that of the jets and air blades. In the past, it was observed that a mismatch of flow rates can lead to excess air spilling from a portal chamber, possibly reducing the efficiency of sampling.

In this prototype, one objective was to guarantee that the blower flow rate could handle the mass flux introduced by firing jets. To accurately measure the flow rate in this prototype, we used a hot wire anemometer. The hot wire was mounted in the circular inlet just before the axial-flow inlet blades of the blower. Here, the flow was more uniform compared to the blower outlet, however the flow was not fully-developed and did experience velocity gradients across the inlet cross sectional area. To correct for these differences in velocity, one must probe the velocity at different points across the inlet area and average the results to obtain a reasonable measure of velocity at a given blower power. Results from these flow rate measurements show that the maximum mean flow rate in the current system is approximately 620 liters per second (LPS).

The programming language LabVIEW was used to control all components of the prototype. Blower input power, blower flow rate, and jet timing and firing configurations are all managed and monitored by the LabVIEW control program. The jet blasting configuration is set by adjusting jet on-time, jet off-time, and number of pulses.

B. *Laser Light Sheet Flow Visualization*

Laser light sheet flow visualization is a technique used to study the fluid motion patterns in an aerodynamic sampling system. This technique is based on the principal of laser light scattering from aerosol droplets when exposed to a thin sheet of laser illumination. To produce a laser light sheet, a 6 Watt 532 nm continuous laser is steered at a 3 mm glass rod. Upon striking the glass rod, the laser beam is spread into a 2-dimensional sheet of light that can be positioned anywhere within the shoe sampling system. A theatrical fog generating machine is used to create an aerosol of micrometer-sized liquid droplets which is then introduced into the light sheet. The aerosol is brilliantly illuminated when it comes in contact with the light sheet and allows one to visualize the flow field as a 2-dimensional cross section. Moving the sheet to different locations and orientations within the shoe sampler provides a complete picture of how the air flow is transported in the prototype. In these experiments, a high speed video camera (Photron APX-RS) was used to capture the dynamic motion of the air. Frames were acquired at 250 frames per second. An example of laser light sheet flow visualization in the shoe sampler operating at 60% blower power is given in Video 1. Here, a vertical sheet bisects the domain of the sampler between the shoes, and the jets are inactive. Refer to Figure 1b for a frame of reference for this video.

Video 1. Example of laser light sheet flow visualization of the bulk flow in the shoe sampler.

Video 2 Video 3 Video 4

Videos 2, 3, and 4. Air blade visualization illustrating the importance of flow rate into the blower. Flow rates into the blower are 240, 410, and 620 liters per second (LPS), respectively.

Videos 2, 3, and 4 show the results of the air blade visualization at three different inlet flow rates; 240, 410, and 620 LPS. The laser light sheet vertically bisects the air blade while the fog generator sits on top of the air blade. When the air blade is pulsed, air entrainment pulls fog into the emitted jet allowing one to visualize the event. To improve the quality of the videos and make them more understandable, shoes are not present in the sampler. Results with and without shoes and legs in the field-of-view were found to be identical.

Flow from the air blade impinges directly onto the floor, and then spreads in all directions (however, the videos only provide 2 dimensions of this effect). The spillage in Video 2 is the most significant due to the low flow rate of the blower. As the flow rate is increased to 410 LPS in Video 3, the spillage is reduced. As seen in Video 4, when the flow rate of the blower is set to 620 LPS, spillage of the air blade is minimized. Visualization experiments like these are critical for understanding the impact of blower flow rate on spillage from the domain.

As demonstrated in the previous videos, visualizing bulk flow patterns and understanding the dynamic flow features in the sampler are critical steps for optimization of the aerodynamic performance of the prototype. However, we must also understand how particles are liberated and transported within the domain of the sampler. To accomplish this, laser light sheet flow visualization and talc powder were used to identify particle transport characteristics within the bulk flow field.

In the following experiments, talc powder was used to seed the flow in a laser light sheet. A cotton (muslin) patch containing milligram-levels of talc powder was taped onto a section of the shoe and then the shoe was sampled within the prototype. The Stokes number of these talc particles is much less than 1.0 because talc powder has a mean particle diameter of 10 µm and the average flow velocity passing by the shoes is on the order of several meters per second. Therefore, these particles are transported efficiently throughout the domain along streamlines in the flow field and similarly represent the motion of real explosive particles in transport.

Videos 5, 6, and 7 show results from flow visualization experiments illustrating particle release and transport within the sampler. The blower flow rate is varied between 240, 410, and 620 LPS. Since the patch is located on the inner heel of the shoe, the air blade is the primary mechanism that will liberate particles from the surface. The goal here is to understand where particles are transported once they are liberated. In the following videos, a vertical laser light sheet bisects the center of the shoe sampler through the air blade. Ideally, particles should be dislodged from the muslin patch and be immediately directed towards the blower inlet (to the left in the videos).

In Video 5, particles are effectively released from the talc patch but are immediately transported away from the inlet. This again illustrates the importance of flow rate to minimize spillage within the sampler. In Video 6, particle spillage is not as dramatic but nonetheless still exists. Video 7 shows that a blower flow rate of 620 LPS completely eliminates the spillage of particles from the inside heel of the shoe. Particles are efficiently removed from the shoe and transported to the inlet. It is now clear that the blower must be operating at 620 LPS to minimize spillage from the domain.

Video 5. Particle release at a flow rate of 240 LPS.

Video 6. Particle release at a flow rate of 410 LPS.

Video 7. Particle release at a flow rate of 620 LPS.

Video 8. Particle release from the outer heel. The laser light sheet has a vertical orientation.

Video 9. Particle release from the outer heel. The laser light sheet has a horizontal orientation.

The next two videos demonstrate particle release and transport from the outside heel of a shoe. As in the previous experiments, a muslin patch with milligram-levels of talc powder was taped onto the outer heel of the shoe and interrogated in the sampler. In this case, the outer jet is the primary mechanism for particle release. Video 8 and Video 9 show particle release from the outside heel with both a horizontal and vertical laser light sheet. In these videos, the blower flow rate is set to 620 LPS.

Notice that, in both Video 8 and Video 9, the talc powder is effectively liberated from the surface of the shoe by the outer jets and transported directly to the sampling inlet. In Video 9, the corner of the sampling inlet domain is visible on the left side of the frame. Liberated particles do not cross this boundary during sampling, thus spillage around this corner does not exist. This is the primary reason that a sampling inlet with a dimensional width of 864 mm was selected. A smaller dimension would constrict the flow and cause particles to spill around this corner, regardless of the flow rate.

C. *Quantitative Particle Release Efficiency*

The flow visualization experiments previously discussed provide a qualitative analysis of the bulk flow field and particle transport within the domain of the shoe sampler. However, quantitative experiments are needed to completely evaluate the sampler in terms of aerodynamic performance and particle removal efficiency. To accomplish this, the particle release efficiency of 45 µm test particles was determined for different locations of the shoe. For these experiments, a black tennis shoe was divided it into 12 different sections, each of which was examined for particle release efficiency. Fig. 2 shows an image of the tennis shoe and its divisions.

To test particle release efficiency, fluorescent 45 µm polystyrene microspheres were placed onto a 2 cm x 2 cm microscope cover slide by sebum transfer. In this approach, an index finger covered with sebum is placed on filter paper containing dry microspheres, and then immediately placed onto the cover slide. This transfers an undefined number of

Figure 2. Tennis shoe used in the particle release efficiency measurements.

microspheres embedded in sebaceous material onto the cover slide. Then, the microspheres on the cover slide are counted using a fluorescent microscope with an automated stage and particle counting software [3]. We then place the cover slide onto a subsection of the tennis shoe with double-sided tape (indicated by the white arrow in Fig. 2).

Once the shoe is loaded with a cover slide, it is placed in the prototype shoe sampler and the sampling process begins. The blower was set to 620 LPS while the two jets and one air blade fire sequentially for three 100 ms pulses, pausing for 50 ms between pulses. This jet blasting configuration is repeated three times. When the sampling process is over, the shoe is carefully removed and the cover slide is counted again in the microscope. Particle removal efficiency is calculated by subtracting the number of particles after sampling from the number of particles before sampling and then dividing by the number of particles before sampling. Each section of the shoe was repeated 5 times.

The results of these experiments, while they cannot be shown here for security purposes, demonstrated the importance of jet orientation in the shoe sampler. Particles can be removed from a surface, even if they are embedded in sticky sebaceous material, as long as the jets apply adequate aerodynamic shear forces to the area. Because of the moderately low particle release efficiencies in this Phase 1 design, the prototype was redesigned by adding more jets and air blades. Results of this Phase 2 design are discussed next.

III. PHASE II PROTOTYPE

A. Shoe Sampler Construction and Description

Particle release measurements from the Phase 1 prototype suggest that more jets are needed to improve the system's ability to efficiency liberate particles from shoe surfaces. A new design has been created to address this need. An image of the Phase 2 prototype is given in Fig. 3.

The new design consists of two air blades and four air jets. The air blades are positioned directly over the tongue of each shoe. The outer air jets remain in the same position as the Phase 1 prototype. Two new inner air jets have been placed on an arm that projects out between the legs of a subject. All jets are vectored 45° downwards and 45° towards the blower inlet. A US patent is currently pending on this design. A previous study [4] demonstrated that particle removal does increase with

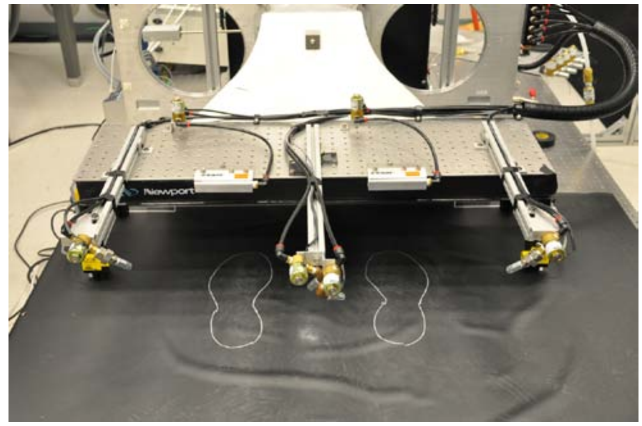

Figure 3. Phase 2 prototype shoe sampler design.

decreasing impingement angle from 90°. They claim that angled impingement combined with downstream collection will yield higher collection efficiency.

The Phase 2 prototype required additional flow visualization experiments to determine the effect of adding new jets to system and their influence on spillage from the blower inlet. Since the number of jets in the system has doubled, one risks overloading the blower inlet with excess air if all jets are fired at the same time. To this end, a new control code was written that enables one to modify jet timing and firing parameters.

The original LabVIEW control code was modified for Phase 2 prototype flow visualization experiments, and allows the user to change jet pulse sequencing before a sampling run. There are five different jet sequences available, each of which was studied to determine the optimal jet pulsing configuration to minimize spillage. After a complete set of flow visualization experiments that explored a combination of number-of-pulses, on-time, off-time, it was concluded that the optimal jetting configuration with the Phase 2 prototype was a sequence with a jet on-time of 50 ms and jet off-time of 400 ms. With this sequence, the cumulative time of jet blasting equals 6.75 seconds.

As mentioned in the Phase 1 prototype evaluation, flow visualization experiments only provide a qualitative analysis of the bulk flow field and particle transport within the domain of the shoe sampler. To evaluate the particle release in the new design, the particle release efficiency measurements with 45 µm particles were repeated at different locations on the shoe. The results indicated that the revised design of the Phase 2 shoe sampler is indeed removing particles more effectively from the surface of the shoes compared to the Phase 1 prototype.

B. Explosive Particle Release Measurements

Particle release measurements using real explosives were also carried out to further investigate the Phase 2 prototypes' ability to remove particles from shoe surfaces. The goal was to compare monodisperse polymer microsphere release to that of a real explosive threat. In these experiments, a known mass of explosive was placed onto a section of the shoe and then sampled in the prototype. To produce a standard test surface for each shoe section, muslin patches containing a known mass of explosives were produced by the Bytac dry-transfer method [5].

Explosive release measurements were carried out is a similar fashion compared to the polymer microsphere release experiments. Here, the patch containing a known mass of explosives was taped onto a subsection of the shoe and then sampled using the jet sequence described above and a blower flow rate of 620 LPS. Once sampling was complete, the swipe was removed from the shoe and analyzed by extracting the remaining material on each patch and then testing the extraction by using a gas-chromatography/micro electron capture detection technique. Each location on the shoe was repeated three times. The results, not shown here for security purposes, do suggest that the removal of real explosive material is significant on all sections of the shoe. As a qualitative observation, the removal efficiency of real explosives is higher than that of the microspheres embedded in sebum.

IV. CONCLUSIONS AND FUTURE WORK

An aerodynamic shoe sampling prototype has been constructed and evaluated in terms of aerodynamic performance. The goal of this project was not to develop a collection device or chemical detector, but rather to design the "front end" of the sampling unit. Much of the work presented here can also be applied to other non-contact sampling approaches, such as cargo and vehicle screening.

The flow rate of the blower is of critical importance in this design. Laser light sheet flow visualization experiments using theatrical fog and talc powder have demonstrated that spillage can be minimized when the blower is operating at a flow rate of 620 LPS. If the flow rate is reduced, then excess air introduced by the jets can overload the system and spill from the domain. This would reduce the effectiveness of sampling and particle collection. At a flow rate of 620 LPS, all particles that are liberated from the shoe surfaces are transported directly to the sampling inlet.

Particle release efficiency measurements of the Phase 1 prototype have demonstrated the importance of jet orientation. The outer jets do an adequate job of removing particles from the outer heels of the shoe, while the single air blade removes particles from the inner surfaces. However, the remaining sections of the shoe did not exhibit sufficient levels of particle release. In the Phase 2 design, the addition of two inside jets has increased the overall particle removal efficiency. Locations with high levels of particle release directly correlate to regions where the jets are vectored. Particles can be removed from a surface, even if they are embedded in sticky sebaceous material, as long as the jets apply adequate aerodynamic shear forces to the area.

The Phase 2 prototype design required an in-depth study of jet timing and sequencing parameters to determine the optimal configuration to minimize spillage. Firing all six jets at once overloads the blower and cause massive spillage from the domain. Several jet sequences were developed and studied using flow visualization to determine their influence on the overall flow field. The number of jet pulses is only limited by the required sampling time for a specific implementation. To a certain degree, the more times the jets are pulsed, the more particles will be removed. Practical limitations in a field-deployed environment would likely limit the overall sampling time to several seconds, meaning that the jets could only be pulsed 3 to 5 times.

The majority of the work presented here focused on the aerodynamic aspects of bulk fluid motion and particle transport within the shoe sampling domain. Several jet blasting configurations that attempted to minimize the influence of the jets on the overall flow field were presented, however they did not specifically focus on the efficiency of particle removal under various jet conditions. Particle release by aerodynamic resuspension is affected by many factors. These include angle of incidence, jet backpressure, number of pulses, pulse duration, and standoff distance. Each one of these factors can influence the effectiveness of particle removal from surfaces and should be investigated in future work.

The successful application of fluid flow visualization techniques and other metrology tools has helped us construct the sampling portion of a shoe screening prototype. We hope that these tools and techniques will be useful to others who are developing next-generation aerodynamic sampling technologies.

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