The Internal Aerodynamics of Cargo Containers for Trace Chemical Sampling and Detection

Michael J. Hargather, Matthew E. Staymates, Matthew J. Madalis, Daniel J. Smith, and Gary S. Settles

Abstract—**Millions of air- and sea-cargo containers enter into and are transported throughout the United States each year. The possibility that some might contain terrorist devices and the impracticability of opening and inspecting them all have become highly charged political issues. However, if the interiors of cargo containers could be quickly sampled for trace explosives without opening them, broad and rapid inspections could be conducted. This would enhance security and allow legitimate cargo to flow almost unimpeded through ports and terminals. Here, we present techniques for nonintrusively sampling cargo containers for trace explosive particles and vapors using external suction devices. The experimental results show the ability to successfully detect explosive contamination and the importance of the internal aerodynamics of the cargo containers. This is studied through flow visualization techniques to reveal the effects of "natural air vents," container geometry, and packing configurations upon the sampling techniques investigated here. A discussion of optimal trace sampling strategies is given based on these results.**

Index Terms—**Air safety, containers, contamination, fluid dynamics, transportation.**

I. Introduction

MILLIONS of air- and sea-cargo containers enter into and are transported throughout the United States each year. Serious concerns exist that a terrorist could smuggle weapons of mass destruction within these containers, which remain largely uninspected. Manual inspection of all containers is virtually impossible since it is estimated that the manual inspection of a single sea-cargo container requires 15 man-hours [1]. For most cargo terminals in operation today, neither the space nor the manpower is available for such inspections. Nonintrusive aerodynamic trace explosives sampling methods, however, might be developed to provide rapid screening processes for these cargo containers.

A recent report by the U.S. Federal Government [2] outlines scientific challenges related to the threat of terrorist-made improvised explosive devices (IEDs) and homemade explosives (HMEs). Among many challenges, two are especially pertinent to the present topic: 1) "Underlying science for the sampling and detection of HMEs and their precursors," and 2) "Development of methods of access (to vehicle-borne IEDs) that are minimally disruptive and have a low probability of initiating an IED accidentally."

Nonintrusive aerodynamic sampling methods interrogate the internal container environment for very small amounts of chemical vapors and/or particles that have contaminated the cargo surfaces. Ideally, these techniques first agitate the internal environment to liberate particles and stir vapors, then collect the air, and ultimately present the contaminated air or particle samples to a detection device [3], [4], possibly following one or more concentration steps. Each part of this sampling sequence has inherent signal losses and limitations which together determine the overall detection system performance. To date the collection and detection stages of these sampling methods have been thoroughly studied, whereas sampling has received little scientific investigation.

Vapor sampling methods have been developed for a wide range of applications, including many aspects of interest to explosive detection [5]. Several methods have been developed specifically for the detection of cocaine, heroin, and explosives within cargo containers [4], [6]–[8]. These approaches all sample vapors within a container by attaching a suction device to a preexisting or intentionally made hole in the cargo container and removing a volume of the internal air. Although these methods all demonstrated successful detection of contraband vapors, limited consideration was given to the methods of removing the sample and no investigations were made into the airflow patterns within the containers themselves. The cited previous work assumes that the contaminant vapors are sufficiently well-mixed and at equilibrium vapor pressure within the container so that the removed air is laden with a detectable amount of vapor molecules, and that the suction device geometry and location do not effect the sampling efficiency. The aerodynamic mixing within the container as a result of the applied suction and the locations of sampling ports have not been considered previously.

Nonintrusive particle sampling methods are less-developed than vapor methods. The primary sampling techniques for particles require direct contact with the surface to be studied [9], and thus are not easily extended to nonintrusive sampling. The present work investigates airborne particle collection

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techniques and identifies guidelines for improving particle collection efficiencies.

The chemical detection of contraband vapors and particles has been thoroughly studied and a wide range of scientific techniques exist for this purpose [10]. The choice of a detection technique is generally independent of the sample liberation and collection methods, and can involve presenting a sample to a trained canine or processing it using a commercial device [11]. The most common detection methods include gas chromatography-mass spectrometry (GC-MS) [12] and ion-mobility spectrometry (IMS) [13], [14]. The present work uses a commercially available IMS detector, the General Electric Security Itemiser[3] (now manufactured and sold by Morpho Detection, Inc.), and does not directly study the detection phase.

The present research is a fundamental exploration of the aerodynamics of the nonintrusive sampling of a closed cargo container for particles and vapor. It focuses on the processes of sample liberation, mixing with the air, and collection. Guidelines for sampling cargo containers are presented based on the fluid-dynamic aspects of the sampling process. Both quantitative and qualitative results are presented, documenting the successful sampling of cargo containers for explosive vapors and particles using nonintrusive sample suction methods.

II. CONTAINER GEOMETRY AND LOAD FACTOR

Today's cargo industry encompasses a wide range of container types, sizes, and commodities. It is important to identify and classify these containers and their typical loading conditions in order to study how to sample them aerodynamically. Three different cargo container types are investigated here: a ULD-3 air-cargo container, a sea-cargo container, and a truck-trailer container.

Loading conditions for all of these containers can either be limited by a maximum weight restriction or by the volume available within the container. The present work is concerned with containers that are volumetrically full because they typically contain boxes or palletized cargo in which a contraband device could be smuggled, as opposed to weight-maximized containers which typically contain heavy unboxed materials such as bulk metals with less ability to conceal contraband.

A. ULD-3 Air-Cargo Container

A Unit Load Device (ULD) is the designation of a container used to hold luggage or freight in an aircraft. One of the most prevalent in use today is the ULD-3, as shown in Fig. 1(a). The dimensions and use of ULD-3s are standardized by the International Air Transport Association (IATA) [15]. The ULD-3 has a standard height of 1.68 m, depth of 1.53 m, base width of 1.56 m, top width of 2.01 m, and total volume of 4.20 m^3. The opening on the side of the ULD-3 is approximately 1.45 m by 1.45 m and is fitted with either a metal bifold door or a canvas curtain door. The canvas curtain door is becoming prevalent in the overall container population, and thus is of prime interest here.

A typical air-cargo container is 75%–85% filled to volumetric capacity, with the remaining empty space located at the top and near the door [16]. The loading typically consists of cargo boxes and luggage with many air gaps between layers, boxes, and the sides of the container. The heavy loading and continuous use of these containers result in routine wear-and-tear damage to the container's thin ($\sim$ 0.4 mm) aluminum sides, as shown in Fig. 1(b). Standardized repair procedures do not exist, thus many containers in use are damaged. The types of damage include missing rivets, holes from forklift impacts, split seams, and indentations on all walls. As described below, this natually occurring damage facilitates the trace sampling of explosives from within these air-cargo containers.

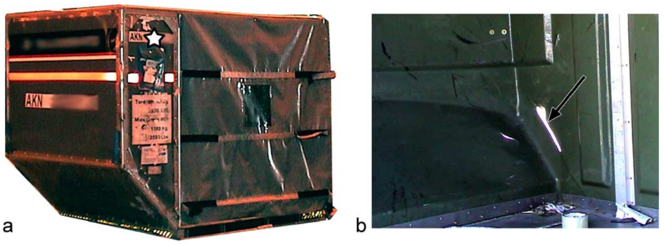

Fig. 1. (a) ULD-3 air-cargo container with a canvas door. The three horizontal straps on the door are made of Velcro and are used to secure the door during transport. The star indicates the location of the sampling port that was added, as discussed in Section IV-A. (b) Typical ULD3 containers are used heavily and frequently sustain routine wear-and-tear damage such as this 150 mm (6 inch) gash near a bottom corner, identified by the arrow.

B. Sea-Cargo Container

Today's sea-cargo industry encompasses a wide range of container types, sizes, and commodities, many of which are outlined by the International Organization for Standardization (ISO) [17]. General-purpose containers, typified by Fig. 2(a) and defined as those that do not carry specialized or refrigerated cargo, are approximately 2.4 m wide by 2.4 m tall and are typically 12 m long [18]. These containers are enclosed and weatherproof, with rigid walls, roofs, and one end wall equipped with doors that open outward [17]. The volumetrically full containers are typically 90% full of palletized cargo, with the majority of empty space located at the top and sides of the container and slight gaps between pallets.

Unlike air-cargo containers, sea-cargo containers are tightly sealed around the access doors and do not typically have significant structural damage leading to air-gaps and leaks. This is because of the harsh sea environment and the need to exclude salt spray from the container. Sea-cargo containers, however, are built with special vents to allow the equalization of the internal and atmospheric pressures during transport. The air-leakage rate through these vents is standardized [17] but the vent design is not, as shown by a small sample of vent geometries in Fig. 2(b). Although every manufacturer has its own vent design, all are roughly similar in shape and function, and conventionally include internal baffles to preclude sea-spray from entering the container [18]. The number of vents is also not standardized, but configurations with either two or four vents are typical. The vents are located on the sidewalls near the container roof in the corners (if only two vents are present, these vents are located in diagonally opposite corners). These standardized vents are the only locations where air can enter or exit a closed sea-cargo container.

C. Truck-Trailer Container

The truck-trailer industry is diverse and contains many different shapes and sizes of trailers designed to transport a vast

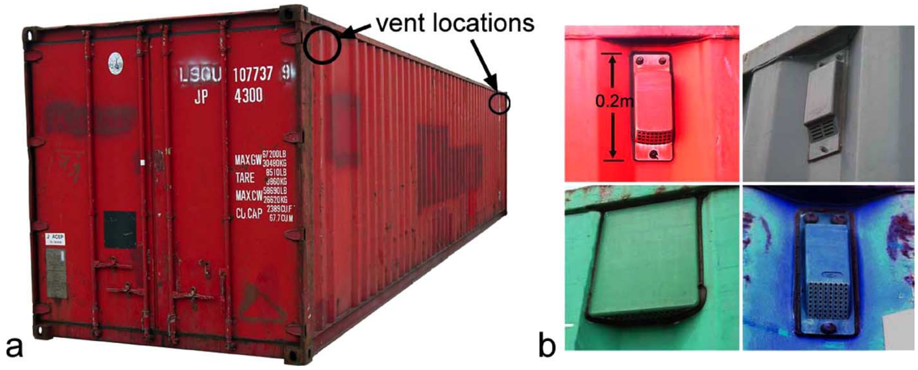

Fig. 2. (a) A typical 12 m long sea-cargo container with the access doors shown and typical vent locations identified. (b) Vent designs vary from container-to-container, but are generally of similar size and provide approximately the same standardized air-leakage rate.

Fig. 3. (a) A 16.15 m (53 foot) truck-trailer with a van-body style and swinging doors. (b) The swinging doors have seals on all four sides with the seal geometry shown in the inset. When closed, the seal compresses and a central air passage is created around the perimeter of the door.

array of cargo [19]. According to an industry database [20], the most common truck-trailer configuration is the 16.15 m (53 ft) long van-body trailer, with a width of 2.60 m and a height of approximately 2.80 m, as shown in Fig. 3(a). These trailers are equipped with one of two door styles, the swinging-door configuration occupying 75%–80% of the population compared to 20%–25% for the overhead-roll-up style. Van-body trailers are used primarily for palletized cargo transport at 80% volumetric capacity average, with the major unoccupied volume found along the sides, top, and between pallets and the door [19].

Ventilation of dry-freight truck-trailer containers is not standardized or required, but is requested by a few customers during construction. Truck-trailer containers are constructed to be watertight but not airtight, thus significant air leakage sites can be found throughout new and old containers, though varying from container-to-container. The primary air-leakage sites are along the seams where the walls meet the floor and ceiling, at joints in the floor (especially near the fifth-wheel hitch attachment location), and along the seals of the swinging doors. The door seals, as shown in Fig. 3(b), are designed to compress to prevent water intrusion. When compressed, an air-path exists along the axis of the seals which provides a significant source of air-leakage from the container volume [19].

III. Trace Chemical Sampling

The present experiments explore the ability to detect trace amounts of explosives or other chemicals located within each of the containers described above. Particle and vapor sources of actual explosives are positioned and moved about the containers to determine collection efficiencies and trends throughout the container volume. For each container, the explosive traces are collected onto a sampling substrate which is then interrogated using a commercial IMS detector described earlier.

A. *Explosive Sources*

The present work uses RDX as the explosive source compound, but in general the presented results are independent of the compound used. RDX is the conventional name for cyclotrimethylenetrinitramine and is also known as cyclonite or hexogen. It is used here because it is a major component of C-4 and several other plastic explosives [21], and most commercial explosive detection devices are able to detect its trace presence at very low mass levels. The explosive sources used here are created from solutions of research-grade RDX dissolved in acetone, obtained from AccuStandard, Inc. These standards are safe to handle and allow explosive sources of known mass to be accurately and repeatably produced.

Explosive particle sources are created through a “dry-transfer” process [16]. The process begins by depositing a known volume of explosive solution (thus explosive mass) on a polished stainless steel plate and allowing the solvent to evaporate, leaving dried explosive crystals on the plate. The explosive is then “dry-transferred” to a gauze pad by rubbing the pad against the plate until all material has been collected on the pad. The pad, now with a known mass of explosive particles loosely attached to it, is then stored in a dry environment with silica-gel packets until it is used.

Non-equilibrium explosive vapor sources are created by flash-heating a known amount of explosive solution using a resistive heating element [18]. The heater is powered by 120 VAC, which quickly heats the 1 cm diameter aluminum element and vaporizes the explosive solution. The element is heated for 20–30 s to ensure that all of the solution has vaporized. All sampling processes began after the explosive was vaporized and the heater was shut off.

Control experiments were performed between explosive collection tests to ensure that the cargo container volume was not contaminated. If contamination was detected, the container and cargo surfaces were wiped with methanol to remove the explosive traces. The collection surfaces and impactors were also cleaned between tests.

TABLE I
GEOMETRY AND FLOW CHARACTERISTICS FOR FULL-SIZE AND SCALE MODEL CARGO CONTAINERS

Cargo container	Volume [m^3]	Volumetric loading [%]	Sampling port diameter [mm]	Suction flow rate [m^3/s]	Differential pressure [Pa]
ULD-3 Air - full-size	4.20	80	50	0.064	0
Sea - full-size	69.12	90	24	0.0061	250
Sea - 40% scale model	4.56	90	9	0.0023	750
Truck trailer - full-size	117.6	80	100	0.050	50
Truck trailer - 17% scale model	5.42	80	18	0.020	100

B. Sample Collection and Interrogation

Explosive samples were collected in this study by applying suction to each container, thus withdrawing an airflow containing the explosive vapors and particles from the container and depositing them onto a sampling substrate by way of an inertial impactor. Particles are collected in an impactor due to their inertia: the particle-laden air that enters the impactor is forced through a sharp turn, which the particles cannot negotiate. Thus, particles with inertia above some designed "cutoff size" impact upon a collection surface.

Inertial impactor technology is well-developed and widely used for the collection of particles from airstreams. Design parameters for the impaction of particles of a given size and density are thoroughly explained by Marple and Willeke [22].

The impactors used here were designed to collect RDX particles with diameters of approximately 1 μm and greater, which is representative of detectable explosive particles [23], and is also smaller than the average particle size on the present dry-transfer patches. The collection cutoff size for each impactor is determined by the particle density, impactor geometry, and air velocity [22].

In each experiment an Itemiser^3 sampling tab is placed on the collection surface of the impactor. Particles are then collected and impacted directly on the sampling tab for analysis in the Itemiser^3. The sampling tab also provides a rough collection surface which helps to reduce particle bounce and blowoff from the collection surface. Sampling tabs used here were made of a metal-mesh material that also has an affinity for explosive vapors.

In general, impactors do not collect vapor. Nonetheless, impaction was successfully used here in explosive vapor collection experiments. This is likely because much of the turbulent airstream through the impactor comes in contact with the sampling tab, thus depositing explosive vapor molecules on the metal-mesh material. Another possible collection mechanism involves explosive vapors condensed upon and bound to airborne dust particles, which are then inertially impacted and sampled.

Once a sample has been collected, the Itemiser^3 tab is removed from the impactor and inserted into the Itemiser^3. The collected sample is then flash-heated and fed to the IMS system, which detects the presence of any trace explosives. The Itemiser^3 uncalibrated output can be used directly to measure relative collected quantities, or it can be calibrated to indicate the mass of explosive detected [16], [18], [19].

The sampling flow rates used here were determined from the scaling analysis and basic considerations for future full-scale field deployment [16], [18], [19]. Future field deployment considerations provided practical limits for the total sampling time, suction device power requirements, and device transportability. All design constraints were applied to the full-scale containers and then dynamically scaled to the model containers tested, as described in Table I.

IV. EXPERIMENTAL RESULTS

The present experimental investigations began with tours of cargo handling facilities where each container type was observed in order to determine typical usage, loading, and physical damage. Discussions with facility personnel were also important to this determination. Initial experiments were performed on containers in the field to provide an assessment of real-world conditions, including the location of natural leakage points.

Experiments on a full-scale ULD-3 container and geometrically-scaled models of sea and truck containers used smoke and laser-sheet flow visualization [24] to determine bulk air motion within each container. The scale models were built to geometrically represent the physical containers, including observed leakage points, and were tested at dimensionally-scaled conditions as summarized in Table I. The flowfield within each container was found to be driven by the "natural air vents" due to seal leakage around the access doors and physical damage locations, resulting in complex flow patterns. Results are presented for containers filled with wax-coated cardboard boxes as "cargo" to provide a fill volume approximately equal to that observed in the field.

A. ULD-3 Air-Cargo Container

Sampling a ULD-3 air-cargo container for trace explosives requires a location from which air can be withdrawn and collected effectively. The lack of an air vent and the varied door configurations on these containers [15] precludes identifying a specific preexisting location on the containers from which to sample. The present research thus determined that sampling ports must be added to these containers for effective cargo screening [16].

Several locations for this sampling port were considered, based on air flow and loading characteristics. It was determined that a sampling port should be located on the side of the access door, above the slanted wall, on the front or rear of the container, as identified by the star in Fig. 1(a). This location would presumably never be blocked by cargo inside the container, and a small amount of interior volume here could be sacrificed to house a self-contained sampling device if desired. Experiments and practicality considerations then determined that a 50 mm diameter port on the front of the ULD-3 in this location is the most effective configuration. The 50 mm-diameter hole was

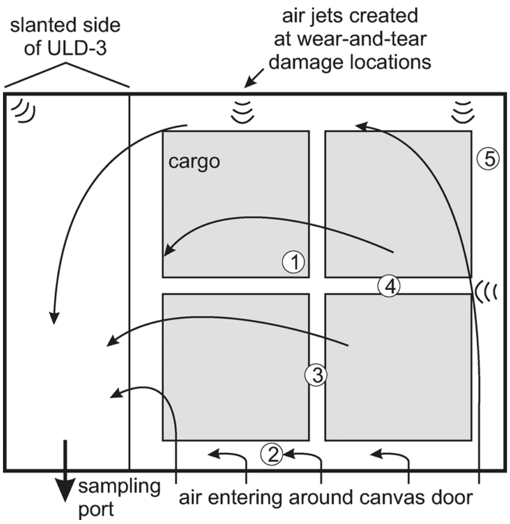

Fig. 4. Top-view schematic of the air flow within a full ULD-3 air cargo container. The majority of the flow is two-dimensional over the top of the cargo. The air that enters along the bottom of the canvas door turns upward and toward the suction port. Wear-and-tear damage results in small "natural" air jets into the container, the majority of the holes being near the bottom of the container. The numbered circles represent locations where particle patch sources were placed.

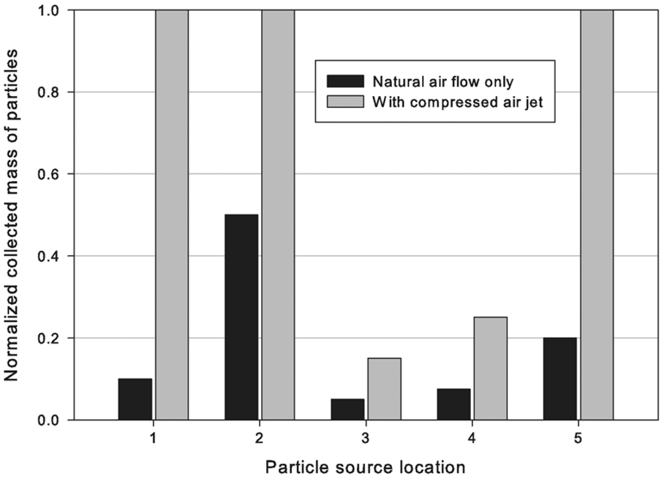

Fig. 5. Normalized collection results for explosive particle sources located within a loaded ULD3 air-cargo container for a 100 s sampling time with only the natural air flow and with the addition of a manually operated compressed-air jet. Each measurement has an uncertainty of about ± 0.1 on the normalized scale.

selected because there is a wide variety of commercially available suction and fan devices with this diameter, thus facilitating the development of a self-contained sampling device.

For the present tests, a commercially available vacuum device was attached to this sampling port on a full-scale ULD-3 and air was removed at a rate of 0.064 m^3/s. At this flow rate, which was the maximum provided by the vacuum device, the static pressure in the container remained at atmospheric pressure (to within gage accuracy of ± 5 Pa). This zero-pressure difference is due to the many air gaps and holes in the container, especially around the canvas door, which allow air to enter the container easily and thus prevent the development of a negative internal pressure.

The air gaps around the canvas door are the primary driver of the air flow patterns within the container; air gaps and holes due to wear-and-tear damage play only a secondary role. Under typical loading conditions, the bulk air flow within the container becomes nearly two-dimensional over the top of the cargo load, with some three-dimensionality at the side over the slanted region (depending on loading). The wear-and-tear damage, typically located near the bottom of the containers, provides air inlets at the base of the cargo load and produces air currents rising along the cargo when suction is applied. The flowfield is summarized schematically in Fig. 4 for an 80% full-by-volume container.

Explosive detection experiments were performed with both particle and vapor sources located inside the ULD-3 air-cargo container. The particle contamination experiments examined the ability to collect particles from locations throughout the container using only the natural air flow created when the suction was applied at the sampling port for 100 s. The 100 s sampling period allows approximately seven air changes within the 20% empty container space, and was determined to be a reasonable length of time for sampling a single container.

Experiments were performed with the particle source placed at each of the five numbered circles in Fig. 4. Location 1 was on top of the cargo in the center of the container, locations 2 and 5 were on the floor and locations 3 and 4 were between cargo boxes at a mid-height. The experiments showed that explosive particles could be collected from each patch location, although there was some variation in the mass of particles collected from the various locations. Normalized trace collection results are shown in Fig. 5. These results are normalized by the largest mass collected in any given test, i.e., the mass collected from source location 1 with compressed air jets.

The results show that the collection efficiency is fairly uniform for particle sources at locations 1, 3, and 4. A slightly higher collection efficiency is observed at location 5, likely due to a local air gap caused by wear-and-tear damage. The increase in collection near this air gap highlights the importance of such gaps in collection, since they produce inwardly directed local "natural air jets" that can dislodge particles throughout the container in locations where the bulk flow does not produce the shear stress required to remove particles from the cargo surfaces [25].

Collection is significantly higher when the particle source is at location 2. This location is subject to the high-velocity jets produced by air entering the container around the canvas door. This high airflow rate effectively removes particles and transports them to the sampling port.

Experiments were also performed using an external compressed-air jet from a nozzle which was inserted into the container and moved manually to improve particle removal from surfaces. This air jet nozzle was mounted on a wand which an operator inserted through a gap in the canvas door and manipulated during the 100 s sampling time. The operator manipulated the air jet by moving it over the top surface of the cargo, directing air downward at the cargo, between boxes, and along the sides of the container. The operator had no knowledge of the location of the explosive source. The results, as shown in Fig. 5, show that the addition of this compressed-air jet significantly improves particle collection. This is because the high-pressure air jet removes particles more effectively from the cargo surfaces due to the high shear stresses it produces [5].

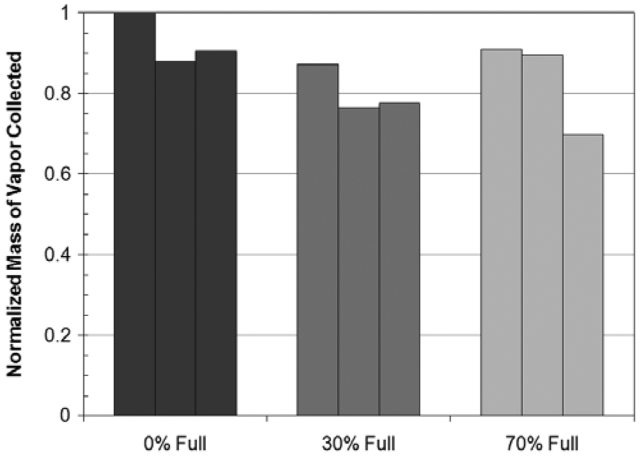

Fig. 6. Normalized collection results for an explosive vapor source within an air-cargo container for variable volumetric loading. Each of the three columns for each loading condition represent a single experiment. The results are normalized by the maximum mass collected in the 0% full container experiment.

The collection remains relatively low when the particle source is between cargo boxes, but a significant improvement over the "natural" air jets is nonetheless observed.

A series of experiments was performed to determine the effect of container volumetric loading on the ability to collect vapor samples from within the air-cargo container. These experiments released RDX vapor within the container and then sampled the air for 2 min before measuring the amount of vapor collected. The vapor source was placed on top of the cargo and centered with respect to the walls of the container. From the nine experiments performed (results shown in Fig. 6), the mass of collected vapor is not significantly affected by the volumetric loading of the container. A weak trend of decreased collection mass with increased loading could be attributed to decreased airflow in some regions of the container and adsorption of explosive vapor by the cardboard "cargo" surfaces. In the empty container, the natural air jets and especially the jets around the canvas door effectively mix the internal volume, thus leading to a large collected signal. As the cargo loading increases, regions of low flow velocity, thus decreased mixing may exist within the container volume which result in lower collected masses of vapor. Adsorption of the explosive vapor signal by the cardboard boxes used here as cargo also decreases the collected signal as loading increases.

Experiments were also performed to determine the importance of when the sampling time begins relative to the time when the vapor generator is turned on. These experiments provide a preliminary understanding of the vapor adsorption to the walls and cargo within a container. As summarized in Table II, the collected vapor signal deceases as the time between vapor injection and sampling increases. This is expected, since the longer the vapor remains stagnant in the container, the more likely it is that it will be adsorbed by the various surfaces within the container. The apparent rapid decrease in collected mass between 10 and 15 min is likely due to a lack of a statistically significant number of experiments for the longer times.

TABLE II
NORMALIZED COLLECTED MASS OF VAPOR FOR A 2 MIN SAMPLING PERIOD BEGINNING AT A GIVEN DELAY TIME AFTER A VAPOR INJECTION FOR A 0% FULL CONTAINER

Time delay (minutes)	Normalized collected mass of vapor
0	1.00 ±0.05
2	0.98 ±0.05
5	0.98 ±0.1
10	0.87 ±0.1
15	0.29 ±0.2
20	0.21 ±0.2

These results apply to the present experiments in which explosive vapor is released at a given time within a container, but may not be pertinent to actual cargo sampling for vapor. In the present work, the sampling time begins shortly after the vapor injection in order to reduce the influence of vapor adsorption by the cargo in favor of vapor entrainment by the air flow through the container volume. In practical applications, the vapor source is more likely to be in equilibrium with the interior container environment, especially for sea-cargo and truck-trailer containers, in which case all sampled air should contain an equilibrium concentration of the contaminant of interest. Future work is recommended on the evolution of the vapor signature within a container, including modeling vapor release from a bulk explosive source and the adsorption–desorption processes by the container walls and cargo.

B. Sea-Cargo Container

Sea-cargo containers include either two or four standardized vents [Fig. 2(b)], which are used here for the explosive sampling procedure. A limited number of laboratory experiments showed that trace sampling is more difficult for the two-vent than the four-vent configuration, thus the present choice of only two vents, located on diagonally opposite corners of the container, is taken here as the primary configuration of interest. These vents account for the only air-leakage into the container volume; the door seals and all wall-floor joints are heavily re-enforced for the sea environment and are quite well-sealed.

A geometrically-similar 40% scale model sea-cargo container was constructed for trace explosive detection experiments. The sampling process was also scaled using the Reynolds number parameter in order to preserve dynamic-similarity and thus the ability to extrapolate model results to full-scale. For the Reynolds number scaling, the length of the container and the flow velocity through the sampling port were used as the characteristic length and velocity. The test conditions for the scale model and the corresponding full-scale parameters are presented in Table I.

The air within the sea container model was sampled by drawing flow through one of the vents by applying suction until the interior pressure was lowered, creating the differential pressure listed in Table I. These experiments used a 746 W (1 hp) centrifugal blower as a suction driver.

Flow visualization experiments were performed with the model 90% full of simulated cargo. The results showed a highly two-dimensional flowfield with the only source of inlet air being the other vent on the container. The flowfield, as shown schematically in Fig. 7, is dominated by a large, fast-moving vortex near the inlet vent and slow-moving bulk fluid motion throughout the rest of the container, ending in potential flow

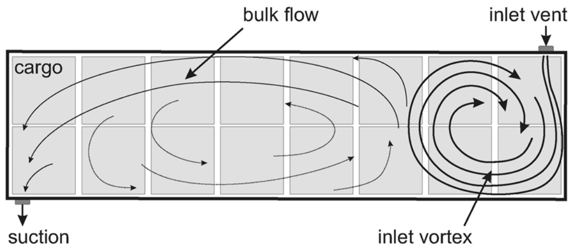

Fig. 7. Top-view schematic of the internal aerodynamics of a 90% full sea-cargo container with suction applied to one of the two vents. The inlet vortex dominates about 30% of the container headspace and is rapidly moving. The remainder of the flow is low-speed circulation and bulk motion toward the vent where suction is applied.

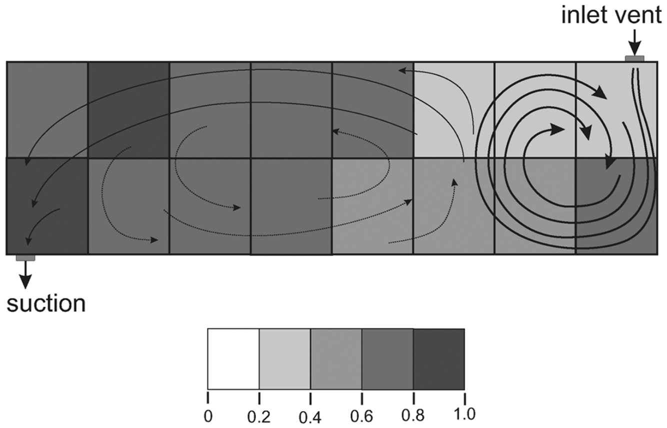

Fig. 8. Top-view of scale model sea-cargo container with contours of normalized mass of RDX collected for a vapor release from within each of the 16 sectors. The general flowfield from Fig. 7 is superimposed on these collection results.

into the vent where suction is applied. Experiments showed that this flow structure is consistent across a wide range of flow rates withdrawn from the container, the only major difference being the velocity range of the flows observed.

The flow visualization shows that a strong jet enters the container at the inlet vent and attaches to the end wall due to the Coanda effect. This resulting wall jet impinges on the wall opposite the inlet vent and rolls toward the suction end of the container. These wall jets drive the inlet vortex shown in Fig. 7. The remaining flow in the container forms a laminar secondary vortex that is counter-rotational to the inlet vortex, directing the bulk flow toward the suction vent.

Initial experiments with RDX explosive particle sources resulted in large-scale contamination of the entire container model. This indicates that the air flow within the container is significant enough to spread particles throughout the interior volume. These particles can then be detected for several subsequent tests. This result was found for explosive particle sources of several different masses, all of which exceeded the detection range of the IMS system. Thus, trace particle sources failed to provide quantitative collection results, and were abandoned in favor of explosive vapor sources.

An RDX explosive vapor source was used to quantitatively map collection trends in the sea-cargo container interior volume. The vapor source was placed on top of the simulated cargo at 16 different sectors of the internal volume. The container air was sampled for 120 s in each test, providing about a 60% air change of the empty container volume. Although a full air change within the container is not achieved during this sampling time, it was found that collection of explosive vapors was still possible. Different sampling times were explored, but the present time of 120 s was chosen because it effectively shows collection efficiency patterns and corresponds to a practical length of time for container sampling in the field. The volumetric flow rate for the sea-cargo container is significantly limited by the tight seals throughout the container and the small diameter holes in the air vents used here as sampling ports.

The normalized results of trace explosive collected from each vapor release site are presented in the contour plot of Fig. 8.

These results show that explosive vapors can be successfully sampled from any location in the container volume by applying suction at a vent, and that there is a correlation between the vapor collection level and the local flowfield near the vapor release point. The strongest vapor signals are collected when the vapor is released near the suction vent, as expected. The lowest collection levels are near the inlet vent because there the vapor signal can be easily entrained into the inlet vortex, causing it to become significantly diluted with fresh air before reaching the suction vent. The signal near the inlet vent may also be depleted due to vapor adsorption by the container walls or cargo surfaces.

C. *Truck-Trailer Container*

Like the air-cargo industry, the truck-trailer community does not require a standard vent on general transport trailers. As before, it was determined that effective explosive trace sampling required the addition of a specific air sampling port somewhere on the trailer. Applying the general aerodynamic lessons learned earlier, the sampling port should be located at the front of the truck trailer volume to maximize the effectiveness of the natural air vents, namely leakage along the container length and loose-fitting rear door seals. A 100 mm diameter full-scale sampling port is suggested here because this is a convenient size that interfaces well with standard fitting sizes in the plumbing industry [19].

A 17% scale model truck-trailer container was constructed for these aerodynamic and explosive detection studies. The model is approximately dimensionally similar to a real trailer, but has a slight aspect-ratio problem due to having a square cross-section instead of the 1:1.1 rectangular section of actual trailers. This small difference was not found to be significant because the 80% volumetric loading condition for the experiments results in a primarily two-dimensional flowfield that is unaffected by the aspect-ratio of the cross section.

The scale model was fitted with the same swinging doors as on an actual trailer, including the rubber gasket seals around the entire perimeter of the door. These rubber seals are critical to the internal air flow and thus were directly replicated on the scale model. The rubber seal geometry is shown schematically in Fig. 3. The model also included randomly-placed "natural air vents" along the floor-wall joints to represent leakage that was observed on full-scale trailers. The air leakage rate of the model was scaled and matched to the leakage rate that was measured on a new full-scale trailer [19].

Flow visualization experiments were performed inside the truck-trailer model to document the flowfield resulting from withdrawing air through the added sampling port. A schematic

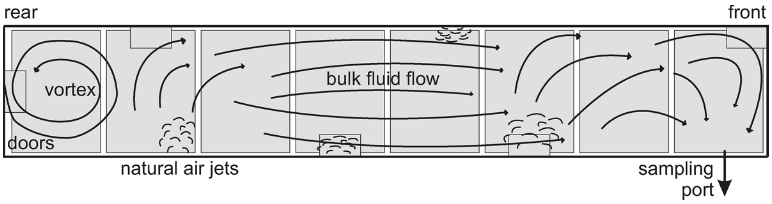

Fig. 9. Top-view schematic of the internal flow patterns in the truck-trailer container when suction is applied to a sampling port. The flow is primarily two-dimensional along the top of the cargo (80% volumetric loading), but flow from around the door seals and leakage at the floor-wall joints provides some vertical motion and mixing. The majority of the flow is laminar bulk motion from the doors forward to the sampling port at the front of the trailer.

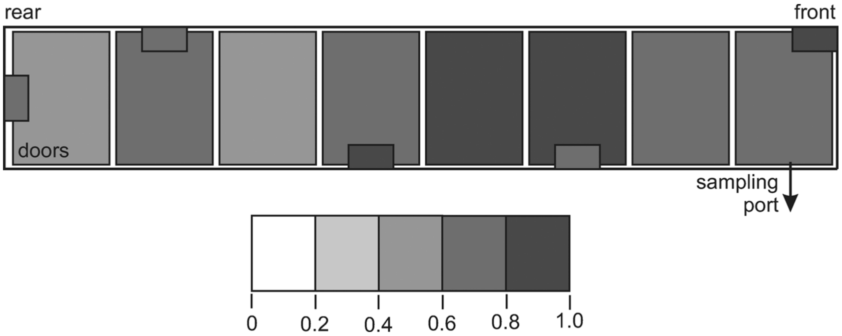

Fig. 10. Top-view of the scale model truck-trailer container with contours of normalized mass of RDX collected for vapor release from each sector. The large, centered sectors represent vapor release on top of the cargo boxes and the smaller sectors are for vapor releases at floor height.

of the observed flowfield for the 80% full container is shown in Fig. 9. The flow is primarily two-dimensional when the container is full, although there are some vertical currents due to the air gaps in the door seals and due to the leakage at the floor-joints.

As in the sea-cargo container, the truck-trailer has a large vortex at the end of the container opposite the sampling port. This vortex develops because the majority of the inlet air passes through the channel on the door seals and is vectored parallel to the door surface, creating a strong wall jet which impacts one container sidewall. The rest of the flow is laminar bulk motion forward toward the suction vent, with a small amount of circulation due to the influence of the vortex created inside the doors. Air gaps along the length of the trailer produce small turbulent jets which provide local mixing but do not contribute significantly to the bulk air motion over the top of the cargo.

Explosive trace detection experiments were conducted using an RDX vapor source which was moved to different locations within the trailer, as with the sea-cargo container. The vapor was released from eight different locations on top of the cargo boxes and from five different locations along the floor of the trailer. The release sectors are shown in Fig. 10 with shading indicating the mass of vapor collected from each vapor release site after sampling for 300 s, resulting in about six air changes within the empty volume. The large sectors are for top-release and the smaller sectors are for the floor-height vapor release. The floor release locations were chosen to directly investigate the influence of the door seal airflow, natural air vents, and a potentially difficult-to-sample corner.

The results show the ability to collect trace explosive vapors from locations throughout the truck-trailer container interior. As with the sea-cargo container, the detected level of trace explosive is dependent on the location of the vapor release, with the lowest signals occurring for vapor releases far from the sampling port. The detected level of vapor did not vary significantly due to the variation in vapor release height, although this result may be confused by the natural buoyancy of the vapor due to the heater mechanism. The results do show that the vapor signal is improved when the release is near a natural air jet, which helps to carry the sample upward and to mix it with the bulk airstream.

V. TRACE SAMPLING STRATEGIES

Knowledge of how the air moves and behaves inside cargo containers can be used to develop logical and effective strategies for trace explosive sampling and container screening. Approaches incorporating the natural internal aerodynamics of each container can efficiently sample these closed-volume container interiors for both particles and vapor without opening the container.

Simple sampling strategies can be developed for vapor collection by applying suction to either standardized vents or added sampling ports on the containers. Vapor collection is simpler in this respect than particle collection, because the vapor signals follow the air patterns directly, thus sampling for vapor requires only knowledge of the airflow. The air flow that develops within a container is primarily driven by large air-gaps around doors and secondarily driven by “natural” air vents created by poor seals or wear-and-tear damage. These “natural” air vents are essential to mixing the interior air and for sampling at locations between cargo boxes and walls of the containers.

The ability to collect vapor signals is also dependent on the vapor source itself and whether it has reached equilibrium within the container environment. The non-equilibrium sources studied here are representative of sampling a cargo container soon after it was loaded with cargo, before an equilibrium vapor concentration has been developed. This non-equilibrium sampling will be affected by vapor adsorption to surfaces throughout the container. Equilibrium sources will not further adsorb to internal surfaces but are expected to have a very low vapor concentration, which will be directly related to the vapor pressure of the source material. When sampling both equilibrium and non-equilibrium vapor sources, it is important to prevent excessive dilution of the vapor signature with clean air. The sampling time should thus be directly tailored to the air flow patterns and flow rates that are generated during the procedure.

Particle sampling within containers requires more consideration, particularly in selecting particle sizes of interest and estimating the ability to remove particles from surfaces. Particle sampling first requires that particles are dislodged from surfaces within the containers, typically requiring high shear stresses on cargo surfaces. The natural air vents throughout the containers, especially in air-cargo containers, are essential for particle removal because they provide high shear stress locally across many of the cargo surfaces. The ability to provide extra shear stress, such as by inserting compressed-air jets, to the internal air flows also helps to dislodge particles from surfaces.

Also, reversing the flow direction through the sampling ports may help to induce high-velocity air flows in different regions of the containers. For sea-cargo containers containing large regions of laminar bulk flow, the sampling process could be improved by sampling alternately from both vents, or by applying air pressure at one vent to stir up the interior then reversing the flow by applying suction.

Particle sampling also requires that the particles are transported by the air flow within the container. The particle transport efficiency depends on the particle density and diameter and the local airflow velocity. Particles are likely be successfully transported throughout the container when the local flow velocities are greater than the characteristic settling velocity for the particles themselves [26], [27]. It can therefore be expected that particles with diameters less than 20 μm will be successfully transported throughout the container environments studied here, which represents the particle diameter range of interest for trace chemical detection [23]. Sampling design thus should focus on the ability to capture small particles, and to enhance internal velocities to carry larger particles, which can improve detection.

The sampling systems can be simply designed around a suction device and a fluid-dynamically-designed inertial impactor, which has been shown to be effective for both vapor and particle collection. The suction devices should be tailored to the application and flow rates required to sample effectively without diluting the trace signal with excess air. Ideally, all of the air initially within the container will be completely sampled without dilution by clean air that is drawn into and through the container. However, the external air was shown to be important for stirring the internal environment, thus a sampling strategy likely needs more than one air volume exchange to ensure effective sample mixture and collection. The number of air volume exchanges should be limited to that required to obtain the desired collection efficiency and total sampling time as needed for a given cargo sampling scenario.

Practical sampling systems can be designed using these principles and fluid-dynamic considerations. Air-cargo container sampling systems could, for example, be built as back-pack-mounted blowers with self-contained sample detection equipment and a jet-blasting wand. Many containers could thus be sampled by one individual walking around a cargo facility. Sea-cargo and truck-trailer containers could be interrogated using vehicle-mounted sampling systems, or by standalone systems which would connect to the sampling ports. These aerodynamic sampling methods could be directly integrated into current bulk-detection systems for a more-complete cargo analysis approach.

VI. CONCLUSION

The internal aerodynamics of air, sea, and truck-trailer cargo containers have been investigated for the development of trace chemical sampling systems. The internal air flow patterns of each container type have been found to be unique and characteristic of the design, construction, and use of each container. It has been shown that it is possible to sample both particle and vapor traces from within each container without requiring either significant human interaction or the opening of the containers. The particle and vapor traces can be successfully removed from the cargo and transported by the bulk air flow from a container when suction is applied to a sampling port.

Air-cargo container flow characteristics are dominated by the large openings around the canvas access doors and the significant wear-and-tear damage to the containers. The natural air vents created by the wear-and-tear damage facilitate trace sampling by producing local air jets which remove particles from hard-to-reach areas during sampling. The "porosity" of the typical used air-cargo container allows a significant air flow rate to be drawn through it in order to successfully remove and transport particles and vapor for effective trace sampling.

Sea-cargo containers are well-sealed and cannot produce such air jets, but applying suction to one of their standardized vents generates an inlet jet that forms a large vortical structure capable of liberating trace particles. The limited air gaps in sea-cargo containers requires a powerful blower to create a significant pressure difference, yielding the flow rates required for effective sampling and especially for particle removal and transport.

Truck-trailer containers have internal airflow characteristics similar to both air- and sea-cargo containers. The inflow of air is significantly limited by the relatively-tight door seals, but natural leakage zones exist along construction seams. The resulting "natural" air jets provide turbulent mixing and particle removal along the length of the container which, combined with the large-scale bulk air motion, allow sampling both particles and vapor. The large volume and long transport times along the length of the container require a longer sampling duration and a reasonable imposed pressure differential in order to produce effective "natural" air jets.

The vapor collection experiments presented here used non-equilibrium vapor sources, which simulate scenarios where a container is loaded and then sampled shortly thereafter. Many real-world applications, however, involve equilibrium vapor sources, where the airborne explosive vapor concentration is unaffected by further adsorption to surfaces within the container. Experiments were not performed with equilibrium vapor sources, but the general collection results are expected to be similar. Equilibrium vapor concentrations, reached in containers over long time periods, are expected to be highly dependent on the vapor pressure of the source material and are likely to have very low concentrations. Future work should investigate the importance of equilibrium sources and adsorption characteristics on surfaces within containers.

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