Venturi Filtration Added to Gaspers, Diffusers, VAV Boxes and Air Curtains

Douglas S. Walkinshaw, PhD, PEng
Fellow ASHRAE

ABSTRACT

Investigations of infectious illness incidents, modeling of air currents and ventilation analysis of virus inhalation in passenger aircraft and other environments, combine to indicate that airborne infectious disease transmission can occur within an aircraft cabin prior to the pathogens reaching the return air grilles and the HEPA recirculation filter or being exhausted overboard. The concept of Venturi gasper filtration device is being investigated to address this. This device will add entrainment capture and filtration at a gasper air outlet. Such outlets, when present, are adjustable nozzles located overhead of the seat beside the reading lights. Experiments and modeling indicates that Venturi gasper filtration will effectively double the filtered air flow reaching the breathing zone of each passenger while capturing many of the airborne particles leaving or entering this zone. The device as conceived can be built into the Personal Service Unit or added as a clip-on to the gasper nozzle. Other potential uses of Venturi filtration include enhancing the air quality performance in a variety of settings of air supply diffusers, variable air volume (VAV) distribution boxes and air curtains.

INTRODUCTION

Virus inhalation predictions using ventilation code requirements and design (longest) exposure periods indicate that the number of infectious aerosol particles inhaled by a group of exposed persons to the same infectious person in a wide body long haul passenger aircraft is roughly twice that in a theater, arena spectator area, grade 9+ classroom or on a national narrow body flight, 3 times that in a commuter train or a grade 3–8 classroom, 4 times that in a bar, restaurant, gambling casino or lecture hall, 5 times that in an office and 16 times that in a subway car.[1] [2]

One of the reasons that inhalation amounts calculated for long haul aircraft are relatively high compared with many of the other environments is their potentially relatively long exposure periods. The exposure time to the same ill person (s) can be up to 15 hours on an international flight compared with up to 8 hours in an office, up to 6 hours in a classroom and 30 minutes in a subway car.

Another reason is high occupancy density. An economy cabin seat in a narrow body jet provides about 37 ft^3 (1.0 m^3) of space per occupant and wide body 50 ft^3 (1.4 m^3) compared with, for example, 53 ft^3 (1.5 m^3) in a train car, 133 ft^3 (3.8 m^3) in a lecture hall, 250 ft^3 (7.1 m^3) in a classroom and 2,000 ft^3 (56.6 m^3) in an office. Of thirteen environments investigated only one, a subway car, can be more crowded in terms of ventilation design code information.[2]

Humidity extremes and the intermixing of persons from different population centers and continents can also increase the risk of airborne infection. The low relative humidity typical in aircraft versus most building environments, for example,

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[1] Walkinshaw, D.S. 2010a. “Germs, flying and the truth.” American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia. ASHRAE Journal, 52(4): 70-73.

[2] Walkinshaw, D.S. 2010b. “Germs, ventilation, occupancy density and exposure duration: a thirteen setting pathogen inhalation comparison.” American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia. Proceedings ASHRAE IAQ 2010.

***Douglas S. Walkinshaw** is president of Indoor Air Technologies Inc., VEFT Aerospace Technology Inc., and ECHO Air Inc., Ottawa, Ontario, Canada.*

is conducive to influenza infections.[3] Low aircraft cabin humidity is partly a result of the low ventilation air humidity at altitude and partly a result of the envelope condensation which occurs at altitude as a result of the cold environment surrounding the aircraft. This envelope condensation not only decreases cabin humidity, it also makes cabin humidification less attractive since raising the cabin humidity coincidentally increases the rate of condensation and the problems associated with it such as corrosion, water damage, electrical shorting, microbial growth, rain in the plane and adding to non-revenue producing dead weight. This condensation also increases as outside air supply rate/person decreases. The reason the condensation occurs is because the cabin air leaks through the cabin liner onto the cold fuselage and skin. The liner cannot be hermetically sealed because it is non-structural and cannot contain the cabin pressure. The problem however can be eliminated by diverting a portion of the pressurized engine bleed (outside) air through the cabin envelope before it enters the cabin. This diversion pressurizes the envelope relative to the cabin by a few Pascal. In this way humid cabin air is prevented from contacting the cold fuselage with the moisture condensing and freezing. Passing engine bleed air through the envelope coincidentally removes some contaminant gases and particles prior to their entering the cabin - the gases by sorption and condensation, and the particles by physical filtering at passageways and inertial deposition.[4] Deposition of particles in the envelope prior to their entering the cabin air is not only safer for the occupants and more readily cleaned off insulation bags during aircraft C check maintenance than degreasing the cabin interior. If the particles are oil based, this deposition also assists in corrosion abatement. The amount of oil deposited from bleed air is not large enough to plug up the insulation. In any case, if indeed the amount of oil deposition from bleed air between C checks were sufficiently extensive to plug insulation bag breathing holes, then it would be straightforward to protect these holes from such deposition.

Passenger aircraft outside air (sometimes referred to as fresh air) ventilation rate capacity varies by model and generally has been decreasing with age.[5 6] This ventilation air is not filtered although some aircraft have catalysts that control the levels of ozone ingested.[7]

Airline operation of the aircraft cabin ventilation system can be at lower than its capacity. In this regard, the Aerospace and Defence Industries Association of Europe recommends compliance with a carbon dioxide comfort standard of 2,000 ppmv.[8] Assuming an ambient CO2 concentration of 350 ppmv and occupant carbon dioxide volumetric production rates at 8000 ft (2438 m) cabin pressure which are 4/3 greater than the sea level rates (i.e. mass production rate is assumed constant with atmospheric pressure) of 0.011 cfm/p (0.31 L/min/p) when awake and (0.0064 cfm/p (0.18 L/min/p) when sleeping, 2,000 ppmv at equilibrium equates to an outside air supply rate of 8.5 cfm/p (4.0 L/s/p) when people are awake and 4.9 cfm/p (2.3 L/s/p) when people are sleeping.[9] Assuming carbon dioxide production rates for these two activity levels do not change with cabin altitude, then 2,000 ppmv at equilibrium equates to an outside air supply rate of 6.4 cfm/p (3.0 L/s/p) when people are awake and 3.7 cfm/p (1.75 L/s/p) when people are sleeping.[10]

ASHRAE standard 161-2007 also provides for lower ventilation rates than most aircraft capacities. It recommends a minimum cabin ventilation rate of 7.5 cfm/person of outside air and a minimum of 7.5 cfm/p of air recirculated through a HEPA filter, for a total of 15 cfm/p of ventilation air supply.[10] The requirement that recirculation air be HEPA filtered and has a minimum flow of 7.5 cfm/p is a first for an ASHRAE ventilation standard and could be restrictive in the sense that larger airflows even through less efficient filters in the cabin itself might produce improved mitigation of the infectious disease transmission concern. For example, while HEPA filters are the 'gold' standard in 0.3 micron and larger particle removal efficiency, the number of 0.3 micron and larger airborne particles removed in buildings with MERV 13 filters (which remove 30% of 0.3 micron and larger particles) is three times greater than in aircraft with HEPA filters (which remove 100% of 0.3 micron and larger particles) because of the 10 times higher recirculation rate per person in buildings.[1 11]

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[3] Lowen, A.C., *et al*. 2007. “Influenza virus transmission is dependent on relative humidity and temperature.” *PLoS Pathogens. 3* (10): 1470-1476.

[4] Walkinshaw, D.S., *et al*. 2000. “An Environment Control System for Aircraft Having Interior Condensation Problem Reduction, Cabin Air Quality Improvement, Fire Suppression and Fire Venting Functions.” United States Patent Office #US 6491254, European Patent Office #EP1140625 (Germany, France, Spain, Sweden, United Kingdom), Canada Patent Office #CA 2256887, German Patent Office #DE69927178.

[5] Hocking, M.B. 1998. “Indoor Air Quality: recommendations relevant to aircraft passenger cabins.” American Industrial Hygiene Association Journal 59:446–454.

[6] Hocking, M.B. 2000. “Passenger aircraft cabin air quality: trends, effects, societal costs, proposals.” Chemosphere 41, 603 - 615.

[7] NRC (National Research Council), Committee on Air Quality in Passenger Cabins of Commercial Aircraft. 2002. “The Airliner Cabin Environment and the Health of Passengers and Crew.” National Academy Press: Washington, DC.

[8] Aerospace and Defence Industries Association of Europe – Standardization (ASD-STAN) EN-4618. 2010. “Aircraft internal air quality standards, criteria, and determination methods.”

[9] ASHRAE. 2007a. “Ventilation for acceptable indoor air quality.” ANSI/ASHRAE Standard 62.1-2007, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia.

[10] ASHRAE. 2007b. “Air Quality within Commercial Aircraft” ANSI/ASHRAE Standard 161-2007, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia.

[11] Walkinshaw, D.S. 2010c. “Germs, flying and the truth.” Letters, ASHRAE Journal, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia. 52(7), July 2010: 13-14.

Research indicates that improvements in controlling infectious aerosol risks in passenger aircraft are needed and that improvements in cabin air circulation and/or filtration/purification arrangements would be helpful. Cabin airflow occurs not only laterally across the plane, but also up and down the length of the plane. For example, recently at an international symposium jointly organized by the U.S. Transportation Research Board and the National Academy of Sciences experts in infectious-diseases and other professionals on the subject discussed the findings of infections and movement of potentially infectious particles between rows fore and aft of the source.[12] Two new studies, following up on several earlier studies including work by Boeing,[13] [14] found that the turbulence induced by the main cabin air vents (not the PAOs) dispersed particle and gaseous contaminants from a single source in a row past others in both directions in the same row and in other rows in measurable quantities six or more rows forward and backward (if there are that many rows available), in both single and double aisle cabins.[15] [16] Flows in the area immediately surrounding a particulate or gaseous air contaminant source were reported to be relatively chaotic, but more ordered when at least three seats away. This chaotic nature makes it difficult to model and predict concentrations in the near-field region.[16]

One investigation found that aisle seats as well as sitting near the source were associated with norovirus illness transfer.[17] Mathematical modeling used to investigate how the SARS virus was transmitted as far as seven rows away in an Air China 117 flight from Hong Kong to Beijing in 2003, found that the wake created by occupant movement in the aisles can carry airborne contaminant this distance and when the movement stops the contaminated air is pushed to the sides and concentration is enhanced for passengers sitting near the aisle.[18] [19] A study by Fabian et al found between <3.2 to 20 influenza virus RNA copies per minute (up to 1,200 virus per hour) in the exhaled normal at rest breath (tidal breathing) of infected persons, indicating that sneezing and coughing are not the only potential source of infectious aerosols. Seventy percent of the 67 to 8,500 particles/liter in the breath had diameters between 0.3 and 0.5 microns, with rarely any larger than 5 microns.[20] By way of comparison, in 1945 Duguid reported 6,200 cold viruses per hour emitted by an infected person at rest.[21] The symposium findings together demonstrated that there are no systems or measures in place to prevent the spread of infectious agents over several rows and that infectious disease pathogen airborne transfer can occur within an aircraft cabin prior to the time the pathogens are directed to the HEPA filters or exhausted outdoors.[1]

Figure 1 illustrates typical locations of cabin air supply slot diffusers overhead of the aisles and in the side walls directing air under the stowage bins, of floor return air grilles and of gaspers mounted in personal service units under the stowage bins. This figure also illustrates the floor air supplies and side wall washing diffusers present in some aircraft which take advantage of the occupant thermal plume air current.

The aircraft ventilation system moves the supply air intentionally in a lateral row-wise circular fashion from overhead and sidewall longitudinal slot diffusers to returns in the same air frame as each window. Based on slot sizes and ventilation rates, exit velocities at the diffuser are in the 500 to 800 fpm (152 to 244 m/min) range.[10]

On some aircraft, there are also personal air outlets (PAOs) or gaspers available above each seat for personal use. Their use is optional and when they are on, they reduce the airflow from the diffusers. Gasper air flows vary considerably between models, number of gaspers in use at any one time, and individual gasper settings. A flow of 3 cfm (1.4 L/s) at 2" WC (500 Pa) pressure is considered to be at the low end when on full.[22] Gaspers are operated by twisting the outlet nozzle to

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[12] Transportation Research Board of the National Academies. 2010. "Research on the Transmission of Disease in Airports and Aircraft." Sept 17-18, 2009, Conference Proceedings 47, Washington, DC.

[13] Lin, C., *et al*. 2005a. "Numerical simulation of airflow and airborne pathogen transport in aircraft cabins - part I: Numerical simulation of the flow field." ASHRAE Trans 2005 Jan; 111(Part 1):755-763.

[14] Lin, C., *et al*. 2005b. "Numerical simulation of airflow and airborne pathogen transport in aircraft cabins - part II: Numerical simulation of airborne pathogen transport." ASHRAE Trans 2005 Jan; 111(Part 1):764-768.

[15] Bennett, J., *et al*. 2010. "Summarizing exposure patterns on commercial aircraft." Transportation Research Board of the National Academies (2010) "Research on the Transmission of Disease in Airports and Aircraft." Conference Proceedings 47, Washington, DC, Sept 17-18, 2009: 15-21.

[16] Jones, B. 2010. "Advanced Models for Predicting Contaminants and Infectious Disease Virus Transport in the Airliner Cabin Environment: Experimental Dispersion Data." Transportation Research Board of the National Academies (2010) "Transportation Research Board of the National Academies (2010) "Research on the Transmission of Disease in Airports and Aircraft." Conference Proceedings 47, Washington, DC, Sept 17-18, 2009: 28-35.

[17] Fishbein, D., *et al*. 2010. "Norovirus Transmission on Aircraft." Transportation Research Board of the National Academies (2010), Research on the Transmission of Disease in Airports and Aircraft, Conference Proceedings 47, Washington, DC, Sept 17-18, 2009:12.

[18] Chen, Q., *et al*. 2010. "Advanced models for predicting contaminants and infectious disease virus transport in the airliner cabin environment." Transportation Research Board of the National Academies (2010), Research on the Transmission of Disease in Airports and Aircraft, Conference Proceedings 47, Washington, DC, Sept 17-18, 2009: 21-28.

[19] Mazumdar, S. 2009. "Transmission of airborne contaminants in airliner cabins."School of Mechanical Engineering, Ph.D. Thesis, Purdue University, 2009

[20] Fabian, P., *et al*. 2008. "Influenza Virus in Human Exhaled Breath: An Observational Study." PLoS ONE 3(7): e2691. doi:10.1371/journal.pone.0002691.

[21] Duguid, J.P. 1945. "The Size and the Duration of Air Carriage of Respiratory Droplets and Droplet-Nuclei", Journal of Hygiene 54:471-479.

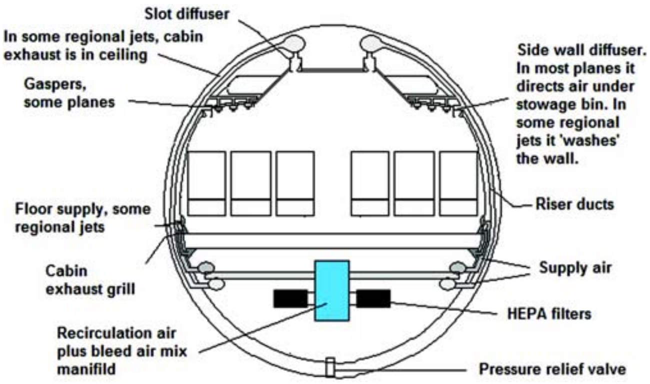

Figure 1 *Aircraft cabin cross section illustrating a cabin environmental control system (ECS) including a cabin ceiling and wall supply and floor exhaust system, as well as some components of a cabin floor to ceiling supply and exhaust system in some regional jets.*[25]

Figure 2 *Personal service unit (PSU) with three gaspers, three reading lights and oxygen masks (not showing) in a narrow body cabin.*

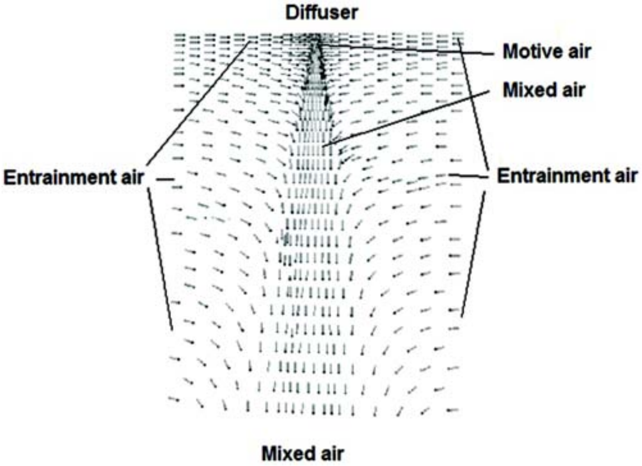

Figure 3 *Mathematical model of the gasper airflow and the lateral entrainment from neighboring areas created. Gasper flow is 3 cfm (1.4 L/s), 95 fps (28 mps) air flow into a cabin at 8000 ft cabin pressure (0.75 atmosphere) illustrating lateral entrainment of air by the motive air flow into a 'motive plus entrainment' mixed airflow in otherwise still air.*

turn the air flow off and on and to adjust the air flow rate. The nozzle direction can also be changed to direct the airflow over the body. In some cases, it can be twisted enough to direct the flow between the occupant and neighbors.

A photograph of a personal service unit (PSU) with gaspers and reading lights is shown in Figure 2.

Black smudges of dust deposition around diffusers are a familiar site. These could be deposits from dust originating in the ventilation air. However, if no such deposits are found in the ducts in 'dead' areas leading to the diffuser, or if there is no such deposition around diffusers in clean, less airborne dust prone rooms (e.g. rooms without carpets), then the dust most likely originated in the room itself. The mechanism for such deposition is the air entrainment by the diffuser air flow. This entrainment is caused by the turbulence and negative pressure at the perimeter of the diffuser airflow stream creating a Venturi effect drawing perimeter ambient air and its dust aerosols to the diffuser air stream where the two combine into one mixture. Entrainment air impinging on the outlet diffuser and adjacent ceiling will deposit some of its dust there. A mathematical visualization of the mixing of motive and entrainment air flows is provided in Figure 3. This entrainment is similarly illustrated in Schlichting and also described in Section 20.3 of ASHRAE Handbook Fundamentals.[23] [24] As with any airflow, the gasper air flow stream has a low pressure turbulent boundary layer which entrains and mixes surrounding air and its contents into the primary airflow stream. Interaction with other air currents in the cabin will affect the entrainment distance and the origin of the contaminants entrained. Experiments and modeling indicate that the amount of air entrained by gasper airflow of 3 cfm (1.4 L/s) exiting at 95 fps (28 m/s) is some 4 or more times this primary (motive) airstream.

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[22] Walkinshaw D.S., R.H. Horstman. 2007. "Personal environment airflow controller." Canada Patent Pending CA2652431, United States Patent Pending US2009163131, European Patent Pending EP2021700, European Patent Office WO2007134443.

[23] Schlichting, H. 1979. "Pattern of streamlines in a circular, turbulent free jet." Boundary-Layer Theory, McGraw-Hill, New York: Figure 24.10, 749.

[24] ASHRAE. 2009. "Principles of Jet Behaviour", American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia, ASHRAE Fundamentals: 20.3-20.7.

As air is not ‘still’ in the cabin, entrainment can include exhaled breath and its contents from occupants six rows away and further.[1 13 14 15]

VENTURI GASPER FILTRATION[22]

Venturi gasper filters use the gasper air supply as the motive air to draw air near the gasper into a housing using Venturi /Bernoulli entrainment. This entrained air is filtered and mixed with the motive air and the combined flow delivered to the space. These gasper filters include a connection to the gasper air supply, a nozzle with one or more jets to deliver this supply air at high-velocity into a mix tube, an entrainment compartment with a filter and/or UV purification (which has not yet been tested) through which the low pressure at the jet boundary draws entrainment air, a mix tube where the primary and entrainment air combine and mix, and an outlet.

Theory[22]

An incompressible ejector equation can be used to predict the entrainment airflow according to the above embodiments.

$$(P_j - P_{amb})A_j + (P_1 - P_{amb})A_1 - (P_2 - P_{amb})A_2 \\ = \dot{m}_2 V_2 - (\dot{m}_j V_j + \dot{m}_1 V_1)$$

where

$\dot{m}_j$ = gasper mass flow, slug/sec
$\dot{m}_1$ = entrained mass flow, slug/sec
$\dot{m}_2$ = total mass flow, slug/sec
A_j = gasper flow area, 0.000529 ft^2
A_1 = mixtube entrance area, 0.011743 ft^2
A_2 = mixtube exit area, 0.012272 ft^2
P_j = gasper exit static pressure, lb/ft^2
P_1 = mixtube entrance static pressure (= P_j), lb/ft^2
P_2 = mixtube exit static pressure (= P_{amb}), lb/ft^2
P_{amb} = cabin pressure, lb/ft^2
V_1 = mixtube entrance velocity, fps
V_2 = mixtube exit velocity, fps
V_j = gasper exit velocity, fps

The filter pressure drop is based on 0.38 inches of water at 780 fpm face velocity:

$$P_{amb} - P_f = 0.15 V_f$$

where

P_f = internal filter pressure, lb/ft^2
V_f = filter face velocity, fps

The mixing chamber entrance velocity is related to the filter face velocity by continuity:

$$A_f V_f = A_1 V_1$$

where ρ = air density slug/ft^3

The mixing and diffusing chamber entrance pressure, P_1 (and the gasper exit pressure) is related to the internal filter, purifier and/or cleaner pressure, P_f, by Bernoulli’s equation:

$$P_1 = P_f - \frac{1}{2}\rho V_1^2$$

where ρ = air density, slug/ft^3

From continuity:

$$A_2 V_2 = A_1 V_1 + A_j V_j$$

The above equations when solved for these system dimensions and a 3 cfm (1.4 L/s) primary air flow and pressure of 500 Pa (2”wc) predict a flow multiplier of 6.0 (total ventilation flow 6.1 times that of the original gasper injection flow) when no filter is present. The flow multiplier at sea level air density is 5.7 for a filter area of 0.25 ft^2 (0.023 m^2) and 4.5 for a filter area of 0.0624 ft^2 (0.0058 m^2) for a filter pressure drop coefficient of 0.15 lb.sec/ft^3 (23.6 Newton sec/m^3). At 8000 ft cabin altitude the flow multipliers are 5.6 and 4.1 respectively.

Experiment[22]

Air was supplied into an experimental apparatus housing in front of and inside a 1.5” diameter mix tube of lengths varying from 2” and up through one or more nozzles at various supply pressures and flows, including 3 cfm (1.4 L/s) at 2” wc (500 Pa) pressure (0.000116 slug/sec) and a jet velocity of 95 fps (29 m/s). Entrainment air was passed through various filter media including a 1” (25 mm) pleated filter with different surface areas, the smallest being for the portable. Respirable suspended particulate (RSP) aerosols were normal room air aerosols. RSP concentrations before and after the filter were quantified with a laser particle counter. Flow velocities and pressure differences were quantified with a micro manometer, pressure tube sensors and a Pitot tube.

The 1” pleated electrostatic filter pressure drop constant was measured as between 0.15 (23.6 Newton sec/m^3) (new filter) and 0.18 lb.sec/ft^3 (28.3 Newton sec/m^3) (used filter) at filter face velocities of 700 to 780 fpm. At these velocities, this filter removed between 22 and 24% of 0.3 micron diameter and larger airborne particles, and 72 and 73% of 1 micron diameter and larger airborne particles. At a V_f of 79 fpm, this filter removed 68% and 74% of 0.3 and 1 micron particles, respectively and at a V_f of 7 fpm this filter removed some 86% and 99% of 0.3 and 1 micron particles, respectively. For a 3 cfm (1.4 L/s), 2”wc motive air supply, flow multipliers up to 6 times were created when no filter was in place and 3.5 for a V_f of 79 fps (24 mps). The portable device had flow multipliers between two and four depending upon filter area. Higher multipliers were obtained with higher supply air pressures and lower supply air flow rates. Single jet supply air entrainment multipliers decreased for a short (2” long) (51 mm) mix chamber and were replaced by a multiple jet motive air supply.

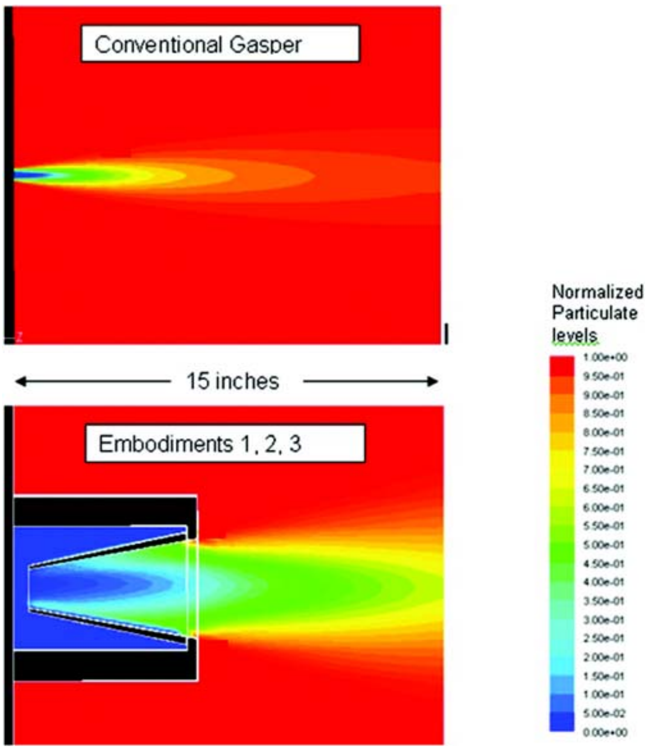

Figure 4 *Mathematical model showing 0.3 micron and larger airborne particulate concentrations with (lower figure) and without (upper figure) filtered entrainment with 60% 0.3 micron filtration. The portable Venturi gasper filtration device can entrain and filter 2.5 times the original 'motive' gasper air supply.*[22]

Mathematical modeling[22]

Commercial CFD software was used for these studies. The CFD model used a second-order upwind scheme. The standard k-ε model was used to simulate the flow field and the relative resistance porosity formulation for the filter media. The motive air flow rate was 3 cfm (1.4 L/s) at 95 fps (29 m/s) with a filter flow resistance pressure drop of 0.15 lb.sec/ft^3 (23.6 Newton.sec/m^3).

Normalized particulate concentrations are shown in Figure 4 without filtered entrainment (conventional gasper) and with filtered entrainment (embodiments 1, 2 3). These values are based on 60% removal of 0.3 micron and larger particles in the entrainment air and a five times flow multiplier. The filtered air flow with the conventional gasper in this model analysis shown is one-fifth that of the filtered entrainment gasper. The higher entrainment gasper air flow emanates from a 1.5 inch (38.1 mm) diameter mix tube outlet. The lower conventional gasper air flow emanates from a typical nozzle

Entrainment and supply airflow velocities and directions are shown for an example portable entrainment gasper filtration device in Figure 5.

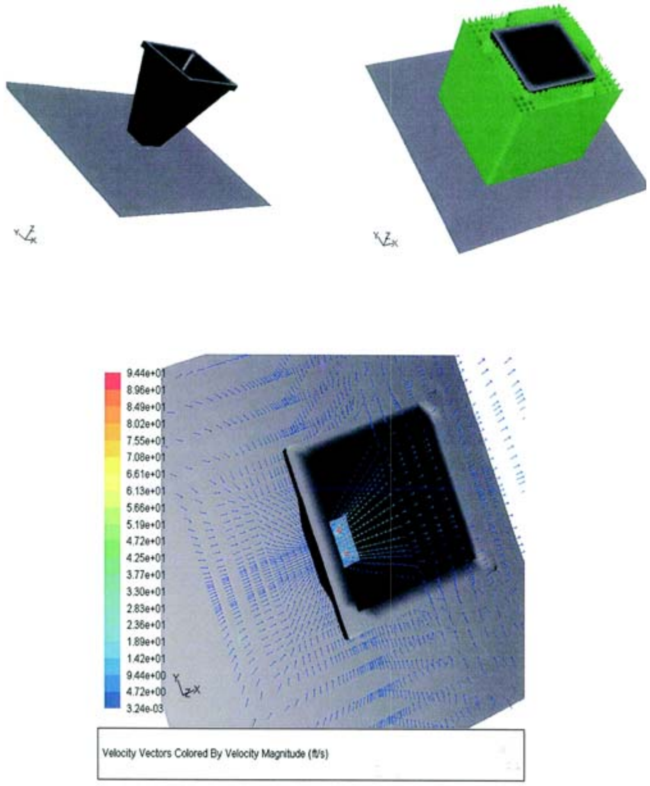

Figure 5 *Mathematical model showing entrainment airflow around an improved portable filtered entrainment device attached over an aircraft gasper supply air. The expanding towards the outlet mix tube is shown in the upper left schematic. The filter is shown in green surrounding the mix tube in the upper right schematic. The lower schematic shows two of the four air supply jets at the entrance to the mix tube. The mixed air supply is shown emerging from the mix tube outlet, and the entrainment air is shown surrounding and coming towards the mix tube outlet.*[22]

Examples of aircraft gaspers with Venturi filtration

Examples of portable and built-in unit designs are provided in Figures 6 and 7, respectively. The example portable gasper is manually fitted to the gasper nozzle. The unit is rotated to turn the gasper nozzle air flow on and off. Air passes from the nozzle through several jet outlets. This increases entrainment in a relatively short 2" (51 mm) long, 1.5" (38 mm) diameter mix tube. When the nozzle is on, ambient air is entrained through the filter and enters into the mix tube at the inlet along with the primary air. Here the primary and entrainment air streams mix before passing through the outlet port. The unit might be made of plastic or flexible rubber. The filter

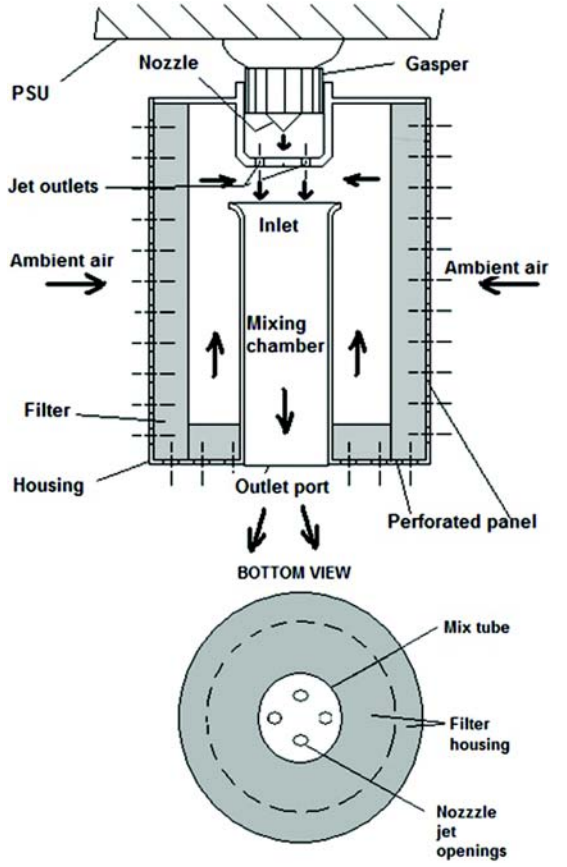

Figure 6 *Schematic of a portable Venturi filtered entrainment gasper design.*[22]

housing can be cylindrical or a hollow cuboid which can be removed and a cylindrical or hollow cuboid filter inserted.

The example built-in to the personal service unit (PSU) gasper includes a fitting with a disk-shaped valve seat which when sealed abuts the upper rim of the orifice. Rotation of the fitting elevates or lowers the fitting thereby opening or closing the opening into the orifice to simultaneously control the flow of air from the gasper supply plenum and allow entrainment, and to also prevent back flow through the mix tube and circumvent the filter when a gasper is not operating. The tubular fitting is fixed mounted to the air supply unit, such that rotation of the unit by grasping the external surface permits the user to rotate the fitting thereby adjusting the flow rate through the air supply unit. Mixing chambers admit the secondary air flow through a secondary opening in the cap which is open only when gasper air is flowing. Rotation of the mixing chamber in one direction thus simultaneously closes the secondary opening and opens the air passages at the valve seat, thereby increasing the primary flow, while rotation in the reverse direction has the opposite effect. Such devices could be useful in other high occupancy density settings such as in buses and trains.

SOME OTHER VENTURI FILTRATION DEVICES[25][26]

There are several other devices where Venturi filtering/purification could provide useful device performance enhancement. These include diffusers (Figures 8, 9, 10), air curtains (Figure 11), and VAV boxes (Figure 12).

The slot diffuser design shown in Figure 8 can be used in place of the aircraft sidewall slot diffusers to entrain and filter air from the breathing zone of groups of passengers and then supply it back to the breathing zone.[25][26] These might also

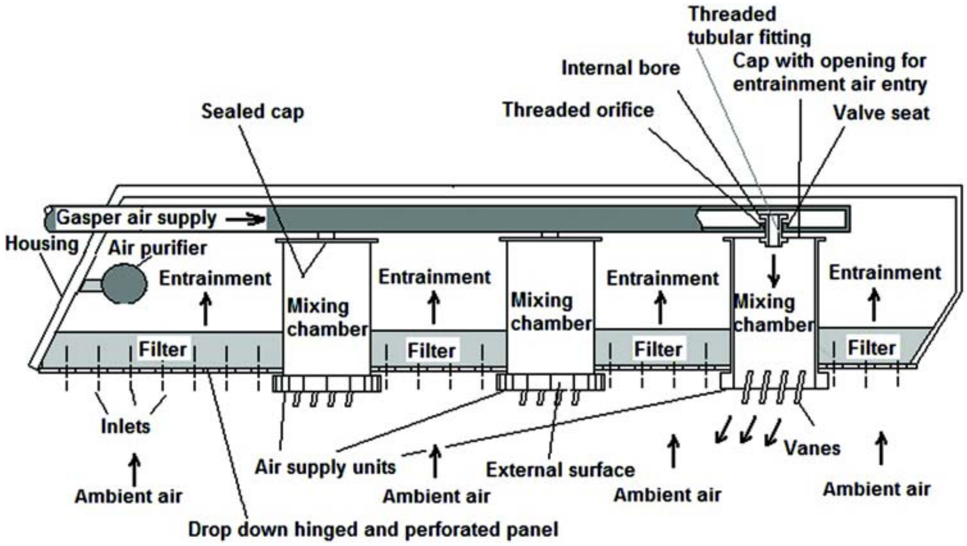

Figure 7 *Schematic of a PSU with built-in Venturi filtration. With 60% 0.3 micron filtration entrains 4 times the original 'motive' gasper air supply.*[22]

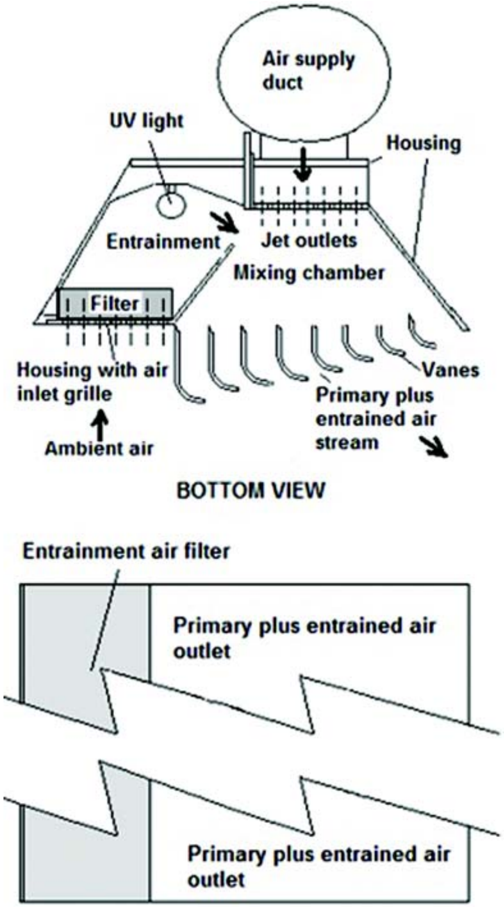

Figure 8 *Slot diffuser with entrainment filtration and/or UV purification on one side the diffuser air outlet. Flow multiplier might be 10 times the motive flow.*[25 26]

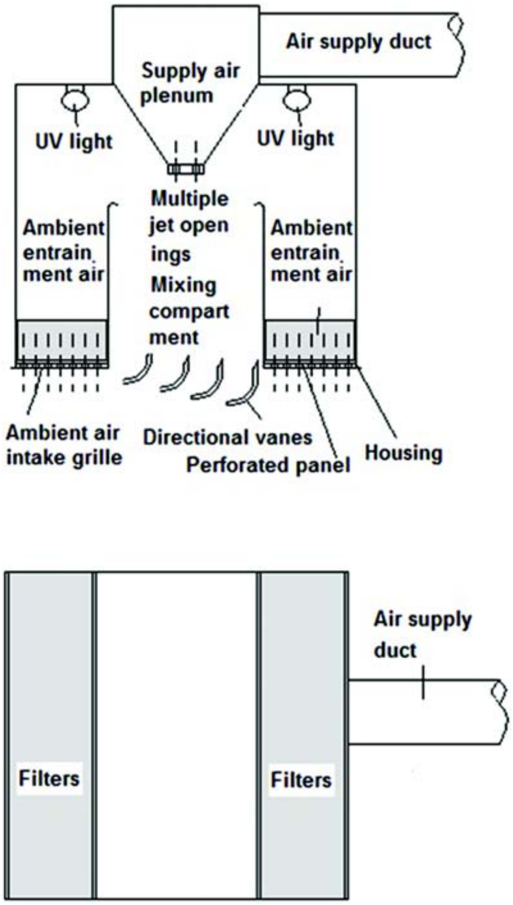

Figure 9 *Slot diffuser with Venturi air filtration and/or UV purification on both sides of the diffuser air outlet. The flow multiplier will be greater with its larger filter area.*[25]

prove useful in building applications such as in meeting rooms.

The slot diffuser design shown in Figure 9 can be used in place of the current overhead slot diffusers to entrain, filter and supply the air above an aisle in an aircraft passenger cabin, a bus, a subway or train car, or in a building above a conference table for example.[25]

The square (could also be round) diffuser design shown in Figure 10 can be used in an office or open office overhead of a desk, entraining and filtering the occupant's bioeffluent from the rising thermal air plume, and circulating the combined clean air around the occupant's space by deflecting off perimeter walls and movable partitions to surround the occupant with much more filtered ventilation air.[25]

The Venturi 'push-pull' air curtain (Figure 11) uses jet entrainment to increase the air curtain blower or compressor motive air supply several times, and to filter and recirculate the air collected at the end of the curtain. It will have a larger and broader initial curtain air flow, and by capturing and recirculating the 'end' of curtain air to the supply side of the curtain, spillage at the end of the curtain into the spaces will be reduced along with energy losses. By filtering and recirculating the air, dust, respirable particulates and flying insect passage (e.g. flies and mosquitoes) through the curtain is prevented. In the case of flying insects the filter could be electronic, killing those that come between two electric wire meshes separated to insect size that are electrified (e.g. to perhaps 2000 volts - a 'zapper'). Such features could be useful in many different applications. Recirculation also facilitates chemical and microbiological sampling at security screening check points, for example.[25]

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[25] Walkinshaw, D.S. 2007. "Entrainment air flow control and filtration devices". Canada Patent Pending CA2655553, United States Patent Pending US2009311951, European Patent Pending EP2035754, European Patent Office WO2007147259.

[26] Horstman, R.H., *et al*. 2008. "Cabin air supply apparatus with filtered air." United States Patent 7789346.

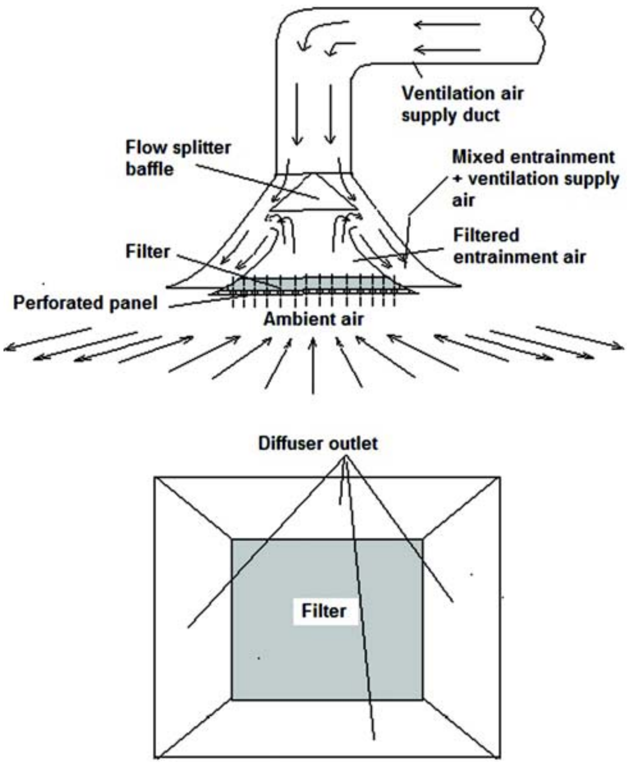

Figure 10 *Example of a square supply air diffuser with Venturi filtration added.*[25]

Variable air volume distribution boxes (Figure 12) have been produced in the past using entrainment to take make-up air from the ceiling plenum to warm up cool supply air and thereby maintain air supply rates to spaces when there is no thermal cooling or heating demand. However, because the entrainment air was not filtered and ceiling plenums are naturally dusty, there were concerns with the quality of the air being supplied. Filtered entrainment would overcome this concern. It would also enable filtration in the occupied space itself. The Venturi VAV box filtration design entrains and filters air on demand enabling a ventilation air supply to the rooms to be maintained even as thermal demand for thermally conditioned air changes. The entrainment dampers can be rotated at a different rate than the motive air flow damper, with calibration in the field to ensure a constant flow rate to a space as thermal demand varies.[25]

DISCUSSION

The entrainment and filtration mechanism for aircraft gaspers can be designed for existing personal services units or new specially designed PSUs. In either case, these installations will have to be certified for vibration, flammability, etc. Removal and replacement of their filters is straightforward. In the case of the built-in filters it involves dropping a trap door to the PSU, bagging the old filter and inserting a new one. Frequency of change might be every three months if Filtrete type filters are used as per their manufacturer's recommendation. This frequency of change would make the performance of the gasper filters and their exchange relatively hygienic in comparison to that of the central HEPA filter for which access is more difficult, and change frequency is part of an aircraft C check which might be approximately yearly.

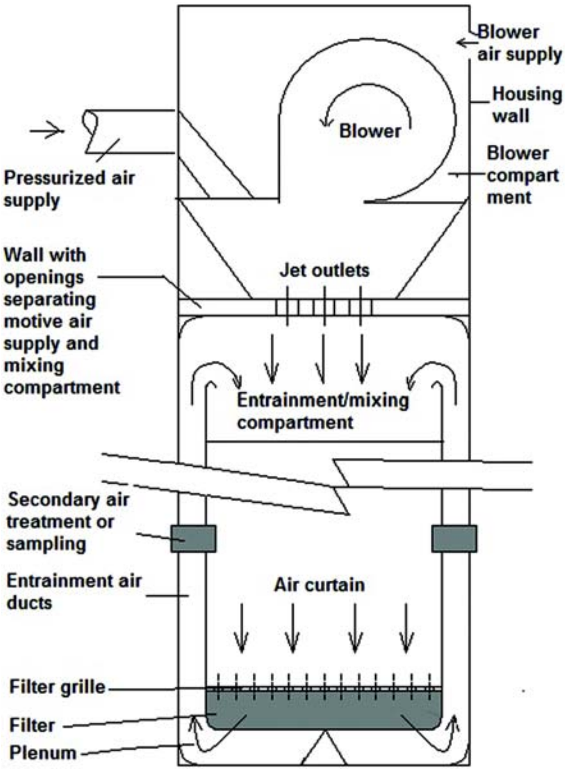

Figure 11 *Air curtain with recirculation entrainment, filtering, sampling (e.g. chemicals for security screening) and possible electronic zapping of flying insects.*[25]

Conventional gasper flow energy is dissipated through entrainment and heating in the space being served by gasper, diffuser and air curtain air flows. It is this energy that is used to create the Venturi entrainment and filtration. No extra motive energy is used. However, in the case of devices with ducted outflows, like the VAV distribution boxes, extra motive energy is required to drive the Venturi entrainment and filtration.

The best filter efficiency is undoubtedly HEPA, but the number of aerosol particulates and pathogens removed from the air is not only a function of filter efficiency. As discussed earlier, air flow rate through the filter or filters, air flow velocity at the filter face, aerosol circulation patterns and filter location within these relative to individual breathing zones, along with filter efficiency, are all important factors and should be taken into account when designing these devices. The location of air filters right in the cabin near each occupant, with 12 CFM/p (5.7 L/s/p) recirculation flows and near HEPA filtra-

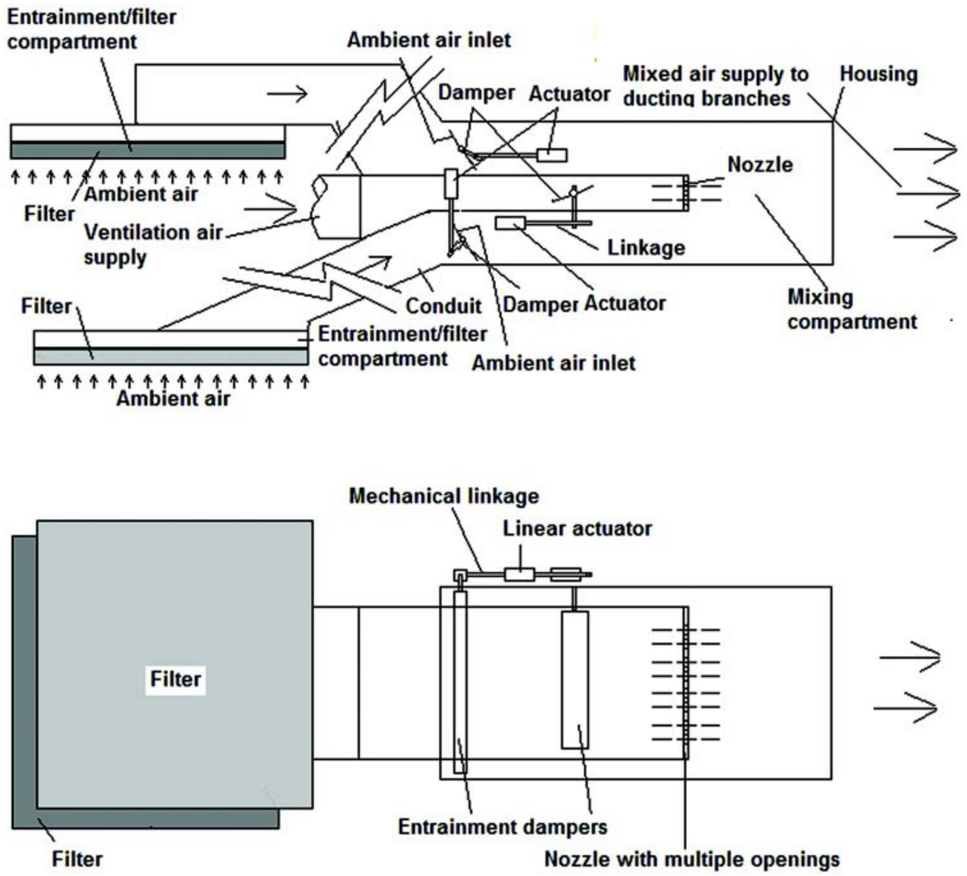

Figure 12 *Variable air volume (VAV) ejector control box which entrains filters/purifies and then re-circulates air from two ambient air sources (e.g. ceiling plenum near lighting and conditioned space). This device is used to supply locally filtered and purified air to diffusers and also to maintain air circulation rates in spaces without using local fans or enlarging the system ducting. Earlier versions were available without filters, drawing their unfiltered entrainment air from ceiling plenums which was of concern because of the dust there.*[25]

tion, will significantly reduce personal exposure to aerosols, whether they enter through the bleed system or are generated by the occupants themselves.

With respect to safety concerns about the protrusion of a plastic or rubber portable Venturi filtered entrainment gasper, another gasper add-on filter device of similar dimensions built of plastic with a ball and socket base and adhesion to the built-in gasper that filters the initial gasper air supply but does not include entrainment filtration, according to the manufacturer has been in use on some 10,000 flights with no reported incidence of head strike or injury.[27] [28]

Venturi entrainment had been added to VAV boxes in the past; however, the entrainment air—taken from the ceiling plenum, for example—was not filtered, leading to air quality concerns. Filtered entrainment overcomes this concern, improving air quality as well as local mixing and thermal comfort. Venturi filtration added to VAV distribution boxes will overcome this concern while providing additional filtered air flow to the spaces being served, thereby enabling the maintenance of constant ventilation air flow rates under variable thermal demand without requiring larger air distribution ducting between the VAV box and the HVAC supply.

Other settings beside passenger aircraft may be able to benefit from the introduction of diffusers, personal air outlets and VAV boxes equipped with Venturi filtration. In designing these devices, increasing the entrainment air filter size where this is practicable has two benefits. It decreases filter pressure drop, increasing entrainment flow rate. It also increases the air passage time through the filter (decreases face velocity) increasing filter efficiency and reducing 'bleed-through'.[25]

The enhanced performance of diffusers and VAV boxes with Venturi entrainment and filtration could be sufficient to reduce or even eliminate the need for central recirculation system filters and air purifiers and indeed in some applications

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[27] Avery, N.H. 2003. "Air filter system". United States Patent 6610116.

[28] Avery, N.H. 2006. "Air filter system". United States Patent 7122066.

the need for recirculation systems not required for spatial thermal conditioning.[25]

A conventional push-pull or re-circulatory air curtain uses a blower to supply to and recirculate air from an air curtain. The Venturi 'push-pull' air curtain uses jet entrainment to increase the air curtain blower or compressor initial or motive air discharge flow coming out of a much broader mix tube several times, and to filter and recirculate the air collected at the end of the curtain. The difference between the two has curtain performance with people passing through and energy efficiency implications, with Venturi entrainment, discharge and recirculation potentially offering significant improvements in both. The broader discharge air stream can be formed by multiple motive jets and shaped to reduce curtain spread angle (e.g. Figure 2C[24]). The addition of filtration in the recirculation air turns these curtains into aerosol air cleaning and flying insect entrapment and desiccation devices. Making the filter electronic reduces filter entrainment pressure loss and when an electronic 'zapper' is added before a particle filter, entrained insects are both killed and body parts collected.

In contrast a conventional air curtain spills all of its discharge and entrained air at the end of the curtain and to prevent drafts, insect or dust entry through such curtains, they are directed at an angle to the passage way being protected (towards the outdoors for example in the case of insect or dust entry protection). This angling creates *inter alia* discomfort for persons passing through and energy losses. Conventional air curtains have been tested as means of either containing or repelling mosquitoes and flies in an aircraft passenger boarding bridge as an alternative to chemical disinsection of the cabin to prevent the spread of malaria and other mosquito-borne diseases between countries. Results showed that horizontal plus vertical or vertical-mounted air curtain units with the airflow directed at a 45 degree angle into the passenger bridge excluded 95-99% of the mosquitoes and 95-100% of the house flies.[29] The broader discharge Venturi entrainment air curtain and its filtration of recirculated entrainment air may be able to achieve similar results with persons passing more comfortably through in either direction without any angling while preventing flying insect escape either onto or off-of the aircraft through its combined barrier and insect capture and destroy mechanisms.

CONCLUSION

Venturi filtration added to gaspers and slot diffusers, VAV boxes and air curtains offers several advantages:

- Diffusers and gaspers can provide a significant amount of local air cleaning and filtering in the vicinity of each occupant's breathing zone at no additional HVAC system energy cost.
- Variable air volume air distribution boxes can provide filtered entrainment air to maintain air circulation in the spaces being served when there is no thermal demand and increase it when there is thermal demand, without the addition of a fan or larger ducting.
- Air curtains can be both comfortable to pass through energy efficient air barriers and dust and flying insect entrainment and capture devices.

ACKNOWLEDGMENT

Raymond H. Horstman is co-inventor of Venturi filtration for aircraft gaspers and diffusers, and did the CFD analysis. His advice and assistance are gratefully acknowledged.

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[29] Carlson, D.A., *et al*. 2006. "Prevention of mosquitoes (Diptera: Culicidae) and house flies (Diptera: Muscidae) from entering simulated aircraft with commercial air curtain units." J Econ Entemol, 99(1): 182-193.