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Low-Cost Wind Tunnel for Aerosol Inhalation Studies*

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A low-cost wind tunnel for aerosol studies has been designed, constructed, and evaluated for aerosol uniformity with 2- and 0.46-µm particles. A commercial nebulizer was used to produce the suspended test particles, and a custom-made, four-hole injector was used to introduce the aerosol into the wind tunnel. A commercially available optical particle counter measured the particle concentration. Performance tests of the velocity profile and particle concentration distribution at two flow rates showed that the system performs well for small particles.

In order to evaluate the health risks to people exposed to airborne dusts it is necessary to determine the efficiency with which particles enter the human airway (inspirability). Research conducted on this issue has involved either experimental measurements or theoretical predictions. In theoretical models, the human head is simulated by a simple shape (e.g., a circular cylinder or a sphere) because of the mathematical difficulties in solving the governing equations for complicated boundaries. Theoretical predictions include, for example, the work of Vincent and Mark[(1)] and Dunnet and Ingham.[(2,3)]

Experimental studies of aerosol inspirability often use life-size mannequins placed in aerosol wind tunnels to directly measure inspirability and to determine the effects of various parameters. Ogden and Birkett,[(4)] Armbruster and Breuer,[(5)] and Vincent and Mark[(1)] have conducted experiments of this kind. Their studies showed that inspirability depends not only on particle size but also on wind speed and direction and on the inhalation rate.

These experimental studies show the importance of wind tunnel test systems for performing measurements of aerosol inspirability. An aerosol wind tunnel is also useful for simulating aerosol exposure at different wind speeds and orientations. This capability can help assess respirator performance, particle sampler behavior, and the sensitivity of aerosol exposure to environmental conditions. Unfortunately, however, past researchers have not described, in detail, the design and performance of the wind tunnels used in their studies. This performance information is important because the spatial uniformity and the steadiness of the aerosol wind tunnel have crucial effects on the reliability of the experiments and on the accuracy of the results.

Ranade et al.[(6)] describe the specifications for aerosol wind tunnels promulgated by The U.S. Environmental Protection Agency (EPA), and they describe the details of an EPA wind tunnel test facility. The EPA wind tunnel is a closed-loop, recirculating type with a working cross-section of 1.52 × 1.22 m. Being closed loop, this tunnel occupies a large space, and it appears to be expensive to construct and maintain. The authors' wind tunnel, which is designed for aerosol inspirability measurements in children of various ages and body sizes, is compact and relatively inexpensive. This paper describes the aerosol wind tunnel, which is constrained by a small budget and limited room space, but which has a performance that meets the EPA specifications. The system is referred to as the UCI (University of California, Irvine) aerosol wind tunnel.

DESCRIPTION OF THE UCI AEROSOL WIND TUNNEL

The wind tunnel system includes a tunnel, an aerosol generator, and a particle injector. The layout of the system is shown in Figure 1. Details of each component are described in the following subsections.

The UCI Tunnel

The aerosol wind tunnel fits in a room measuring 5.5 × 3 m and allows for access to three sides. These close confines dictated a 4.25 × 1 × 1 m open-circuit wind tunnel design. An open-circuit wind tunnel has advantages in addition to size over closed-circuit designs, such as lower power factor (the ratio of input power to the rate of kinetic energy flux in the working section), the absence of corner vane resistance, and decreased working-section turbulence because of the lower turbulence of the entering air stream.

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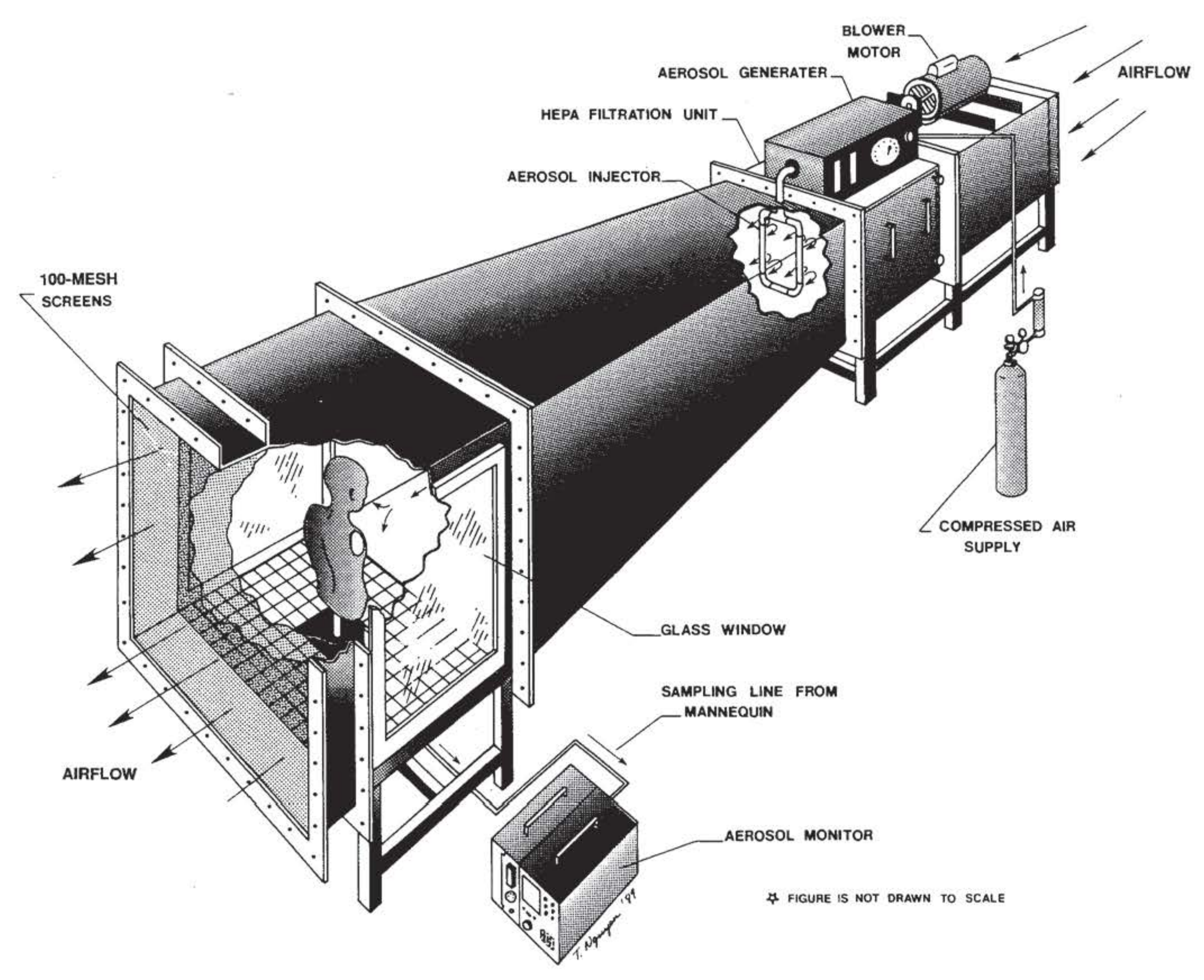

FIGURE 1. An isometric projection view of the aerosol wind tunnel, particle injector, and particle counter

The UCI tunnel design is shown in Figure 2. The design consists of four main sections: a blower, a filter, a diffuser (transition), and a working section. The tunnel was designed to have a working section of at least 1 m^2 to provide less than 20% blockage area for an adult male head and torso mannequin.

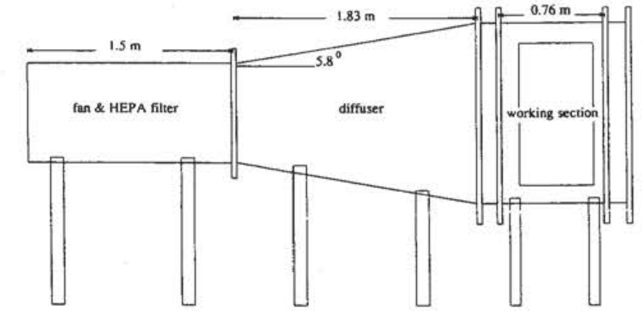

FIGURE 2. Physical dimensions of the UCI aerosol wind tunnel

Each diffuser section wall has a 5.8° angle to make the transition from a 0.37 m^2 blower to the larger test section. The expansion angle of the diffuser is kept below 7° to prevent the possibility of a separation flow along the wall, which causes turbulent flow downstream of the separation.

A 0.75-kW motor powers a centrifugal fan (Lan-Air Supply Co., Santa Ana, Calif.) capable of moving 1.42 m^3/sec air against a pressure drop of 0.248 kPa. The tunnel sits on a wood frame with 0.6 m clearance from the floor to provide a convenient, accessible height for running experiments. Instead of using honeycomb to smooth the flow velocity, a high-capacity (0.94 m^3/sec against 0.335 kPa pressure drop), high-efficiency (99.97% efficiency for 0.3-μm diameter particles) particulate air (HEPA) filter (Air Conditioning Specialties Co., La Habra, Calif.) between the blower and diffuser entrance removes ambient particles and smooths out velocity variations generated by the fan. To avoid unsteadiness and turbulence in the working section, two 100-mesh screens 15 cm apart are mounted between the diffuser and the working section. As described by Bradshaw and Pankhurst,[7] the 15-cm separation is necessary to allow turbulence in the wire wake of one screen to decay before the next screen is reached. Two additional screens are installed behind the working section to eliminate any perturbation caused by air currents in the tunnel room. A 1-m space between the tunnel outlet and the end wall of the room helps eliminate backflow air to the test region. Both sides of the working section contain removable glass windows to allow for photography or other optical access. The windows are easily removed for physical access to the test section. The finished tunnel provides airspeeds up to 1 m/sec. Except for the blower, HEPA filter mount, and windows, the tunnel was constructed of 19-mm thick finished plywood. The wind tunnel material cost is about $2400, with the cost breakdown shown below. After all of the parts were available, the wind tunnel required approximately 15 hr of assembly time.

• Blower section	$800
• HEPA filter section	600
• Screens	150
• Wood and cutting	800
• Gaskets, hardware, etc.	50

Aerosol Generator

In order to obtain a monodisperse aerosol, suspensions of uniform latex particles (Duke Scientific Corp., Palo Alto, Calif.) were nebulized. A sequence of nebulization, dilution, and charge neutralization similar to that described by Raabe[8] was used. Aerosols were produced with a commercial Collison-type, compressed-air, fluid-nebulizer aerosol generator (Model 7330, Environmental Research Co., St. Paul, Minn.). The generator contained a dryer, a pressure regulator, an absolute filter, an adjustable valve, two precision flowmeters, a fluid atomizer, and a radioactive 85-Kr deionizer. This device is schematically illustrated in Figure 3. Compressed air, after passing through a

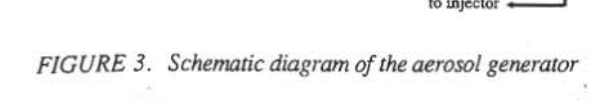

FIGURE 3. Schematic diagram of the aerosol generator

chemical dryer, pressure regulator, and filter, is divided into atomizing air and diluting air. Atomizing air entrains an aqueous droplet suspension of monodisperse polystyrene latex (PSL) spheres that have been atomized through a three-hole venturi nozzle, sprayed against a baffle, and mixed with dilution air. This nebulizer has been described in detail by May.[9] After mixing with dry dilution air, the aerosol charge is neutralized, and the particles pass into a particle injector mounted in the diffuser section of the wind tunnel. This system provides particles ranging from 0.2 to 5 μm in diameter.

Particle Injector

The particle injector introduces particles into the wind tunnel immediately downstream of the HEPA filter. Several arrangements of aerosol injector holes were evaluated to achieve a uniform aerosol distribution across the entire test section, or at least over a cross-section larger than twice the blockage area of the largest mannequin (head with torso). This evaluation showed that a single-hole aerosol injector in the diffuser section produces an aerosol cloud, with an approximately circular cross-section, at the midplane of the test section. It was also noted that the aerosol concentration fell off approximately linearly with radial distance from the center of the cloud. This linear concentration decay was measured to be about 2% per centimeter radially outward from the center line. A simple computer program was then used to superimpose aerosol concentrations from each hole in multiple-hole aerosol injector arrays. The program assumed the measured 2%/cm single-hole aerosol radial concentration gradient for each hole in the array. Various aerosol injectors and various spacing were simulated, and a four-hole injector was predicted to produce acceptably uniform aerosol concentration in the test section. On the basis of this prediction, a four-hole injector with aerosol injector holes 1 mm in diameter was made of 2-cm copper tube. As predicted, this injector produced acceptable particle concentration uniformity in the wind tunnel.

ASSESSMENT OF PERFORMANCE

Velocity Profile

The measurements of airspeed across the tunnel section were carried out with a commercial air velometer (ALNOR Instrument Co., Niles, Ill.). Figure 4 illustrates the velocity profile over the central 48% of the wind tunnel cross-section measured in the longitudinal center of the working section. This central 80 × 60 cm section had a mean velocity of 0.9 m/sec. The numbers marked on the contour lines are the percentages of velocity deviation from the mean value. For this simple and inexpensive wind tunnel configuration, the uniformity of flow is acceptable. The contour map indicates a horizontal velocity gradient in the test section that apparently results from the uneven discharge of the blower through the HEPA filter. Despite this gradient, however, the variation of wind speed across the test section meets the wind speed requirements specified by EPA, with less than ±10% variation of the mean wind speed in the test section.

The blower had two speeds (via pulley adjustment); consequently, airflows down to 0.6 m/sec were also possible. Figure 5 displays the velocity contour plot for the wind tunnel at this lower speed. The velocity field is qualitatively similar to the field in the higher speed case. In the future, the existing blower may be replaced with a larger blower to vary the wind speed over a larger range and to help reduce the velocity gradient in the tunnel.

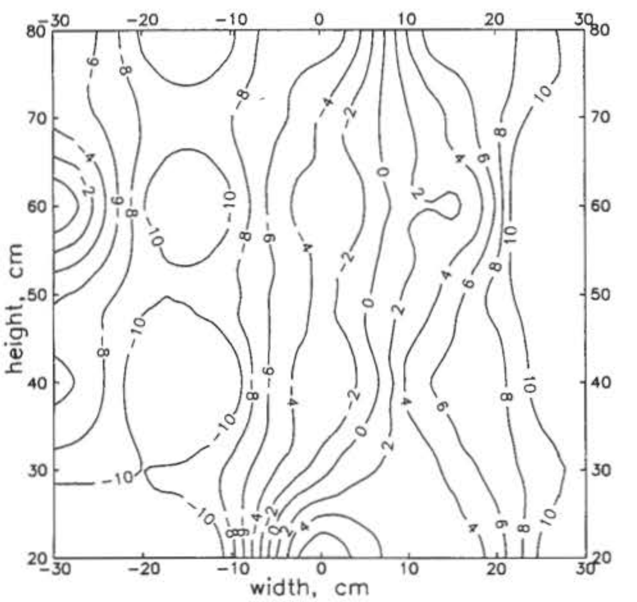

FIGURE 4. Air velocity uniformity in the test section of the wind tunnel. The contours show the percent deviation from the mean velocity of 0.9 m/sec.

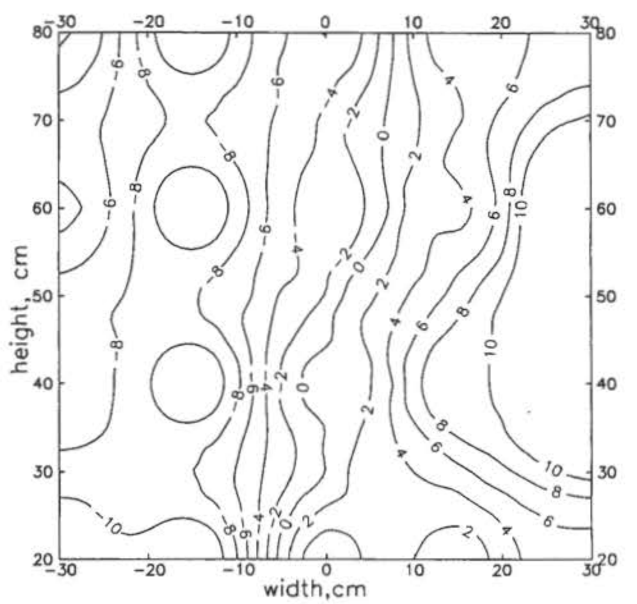

FIGURE 5. Air velocity uniformity in the test section of the wind tunnel. The contours show the percent deviation from the mean velocity of 0.6 m/sec.

To assess the stability of the velocity field in the wind tunnel, the absolute variation in velocity at each measurement location was monitored for a 20-sec period. The absolute variation was less than 3% at all locations. To assess the reproducibility of the velocity field, velocity profile measurements were repeated after 6 months and after 1 yr. The mean velocity over this time changed by less than 5%, and the contour maps showed the same spatial

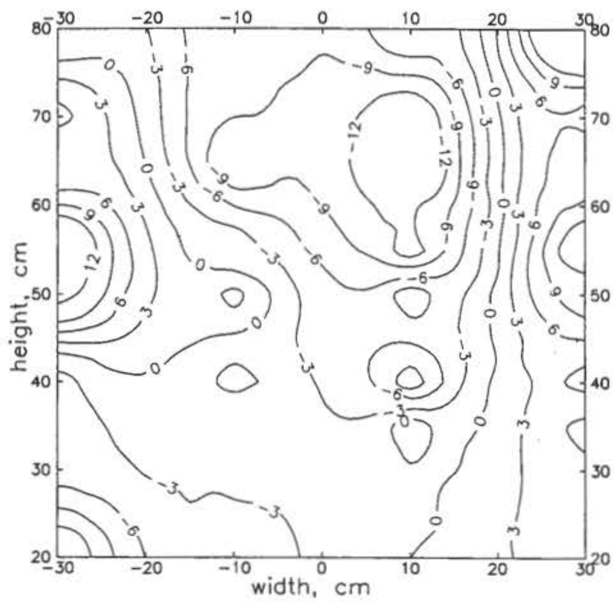

FIGURE 6. Aerosol concentration uniformity across the test section at a mean wind speed of 0.9 m/sec. The contours show the percent deviation from the mean concentration.

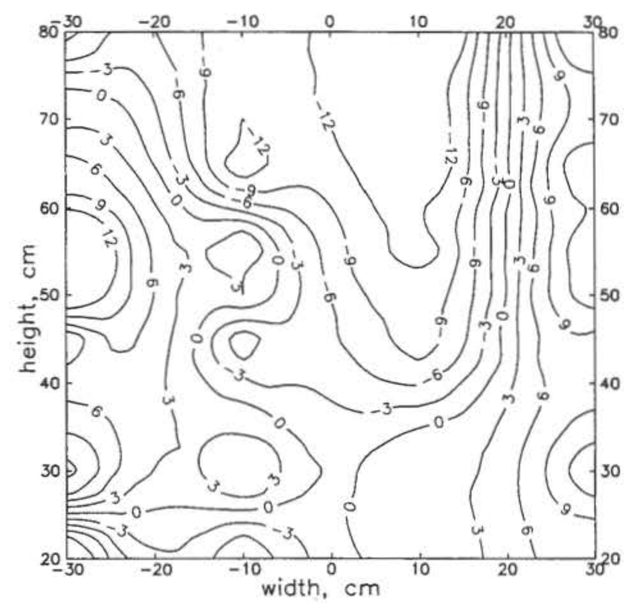

FIGURE 7. Aerosol concentration uniformity across the test section at a mean wind speed of 0.6 m/sec. The contours show the percent deviation from the mean concentration.

velocity variations. These measurements indicate that the velocity field of the wind tunnel is both stable and reproducible.

Aerosol Concentration

Aerosol concentration within the tunnel was measured with a commercial isokinetic inlet velocity sampler connected to an optical particle counter (Model 8060, Climet Instrument Co., Redlands, Calif.) at a suction rate of 28 L/min. Figures 6 and 7 show the measured concentration profile generated by a four-hole injector by using 2.02-µm (manufacturer's nominal diameter) polystyrene latex particles and wind speeds of 0.9 and 0.6 m/sec, respectively. The axial measurement location is the same as that for the velocity profiles of Figures 4 and 5. Each concentration measurement represents an average of four 1-min particle counts with the Climet particle counter. The standard deviation over these four counts was always less than 5% and was usually less than 2%. Again, the numbers on the contour plots represent deviations from the mean value.

Figures 6 and 7 show substantial spatial variation in particle concentration. Even over the dimension of a typical head (about 15 cm) the particle concentration can vary by 5%. The EPA, however, requires only that the variation in the sampling zone be less than 10% of the mean concentration. The authors' wind tunnel easily meets this specification for 2.02-µm diameter particles. The sampling zone defined by EPA is a rectangular area having a horizontal dimension not less than 1.2 times the width of the test sampler and a vertical dimension of not less than 25 cm. The test sampling zone in the case of an adult mannequin head is approximately 25 cm high and 20 cm wide. The area in the wind tunnel test section between the position of −15 to 5 cm horizontal and 30 to 55 cm vertical provided a sampling zone with variation of particle concentration within the EPA-required 10%. The particle concentration measurements were repeated several times to ensure reproducibility.

The spatial distribution of particle concentration for 0.46-µm diameter particles was examined by mixing this particle size with 2.02-µm particles and then measuring the concentration of both sizes independently but simultaneously. The ratio of 0.46-µm particle concentration to 2.02-µm particle concentration was constant to within ±2%, indicating that the wind tunnel does not have size-selective flow characteristics.

Ideal inspirability studies include particles up to 60 µm in diameter. For particles larger than 5 µm diameter, however, significant particle loss occurred inside the injector, which prevented reasonable particle delivery. Hence, although the velocity characteristics of the wind tunnel are adequate for large particle studies, spatially uniform concentration of very large particles will require modifications in the particle injector system. In its current configuration, the wind tunnel/particle injector combination is suitable for studies involving inspirability of relatively small particles and studies of respirable particles at low wind speed.

CONCLUSIONS

A low-cost, compact wind tunnel for aerosol studies that meets the performance requirements of the U.S. EPA as described by Ranade et al.[6] was designed and constructed. Performance tests of the wind tunnel show that the spatial variation of the velocity across the working section is within ±10% for mean flows of 0.9 and 0.6 m/sec. A commercially available, Collison-type aerosol generator produced small particles that were introduced into the wind tunnel through a four-hole injector. This system provided a reasonably uniform particle concentration distribution for particles less than 2 µm in diameter. The uniform particle concentration region can cover an adult mannequin head or a small head and torso to perform inspirability experiments. Even with its low cost, the UCI aerosol wind tunnel has a particle concentration uniformity that meets EPA requirements for such wind tunnels.

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