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Preliminary Study for a New Dust Wind Tunnel: Small Scale Testing

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Abstract. *Wind tunnel testing is important for aerosol sampling studies. The goal of this study was to design a wind tunnel that meets the USEPA requirements: the maximum deviation of both the aerosol concentration and the velocity from the mean should be less than 10% at the cross sectional working area. Several challenges are associated with the wind tunnel design. First, the design of the air mixer is difficult since there is few scientific relationship between the mixing efficiency and the mixing distance. Second, if a big wind tunnel is built using a poor design, it will be expensive and time consuming to modify or rebuild it. Therefore, a 1:5 scale tunnel was built to predict the behavior of the full-scale module. From the experiments carried out in the small wind tunnel, a Generic Tee Plenum System (GTPS) was found to be a good mixer with a coefficient of variance (COV) of 2.5% in the testing area. When employing a modified shape inlet to the GTPS or adding a double air blender downwind of the GTPS, the deviation of the velocity from the mean was found to be less than 10%. Based on the result of the small scale test, a full-scale wind tunnel has been built. It is expected that the full-scale wind tunnel will meet the USEPA's requirements with few modifications.*

Keywords. Dust wind tunnel, small-scale test, uniformity of aerosol cloud, uniformity of wind speed, GTPS, air blender

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Introduction

The dust wind tunnel used in aerosol studies is designed to achieve a uniform aerosol concentration and air velocity close to ambient aerosol concentrations and wind speeds. If the wind tunnel is designed properly, it can provide well controlled experimental conditions for aerosol sampling investigations (Ranade et al., 1990, Witschger et al., 1997). The wind tunnel design described herein is used to evaluate PM_{10} or $PM_{2.5}$ samplers and must satisfy the performance requirements for the uniformity of the wind velocity and aerosol concentration as stated in Title V (USEPA, 1987). The performance requirements are summarized in Table 1. Unlike the aerodynamic wind tunnel, which requires low turbulence, there is not any requirement stated in Title V on the turbulence level of the dust wind tunnel since dust wind tunnels simulate the aerosol concentration and wind speed in the surface layer of the troposphere rather than in the stratosphere.

Table 1. The specified requirement for the performance of wind tunnel in the testing area by USEPA (USEPA, 1987)

Parameters		**PM_{10} Requirements**	**$PM_{2.5}$ Requirements**
Air Velocity	*Uniformity*	$\pm$10% for 2, 8 and 24 km/h	$\pm$10% for 2 and 24 km/h
	Measurement	1) Minimum of 12 test points 2) Monitoring techniques: precision $\leq$ 2% ; accuracy $\leq$ 5%	
Aerosol Concentration	*Uniformity*	$\pm$10% of the mean.	$\pm$5% of the mean
	Measurement	1) No less than 5 evenly spaced isokinetic samplers 2) The sampling zone shall have a horizontal dimension not less than 1.2 times the width of the test sampler at its inlet opening and a vertical dimension not less than 25 centimeters	
Turbulence	*Uniformity*	No requirement Former studies indicate that turbulence higher than 7% ~8% will affect the sampling efficiency (Wiener et al., 1988)	
Particle size	*Measurement*	Accuracy $\leq$ 0.15 µm; size resolution $\leq$ 0.1 µm	

To design a wind tunnel that satisfies the USEPA requirements, several challenges must be overcome. Achieving the required aerosol cloud uniformity is the first and biggest challenge. To achieve the aerosol cloud uniformity, we must either design a high turbulence area in the tunnel or create the turbulence using some other technique. The USEPA tunnel for testing PM_{10} sampler used a muffler and a counter mixing fan (Ranade et al., 1990). Another wind tunnel developed by Witschger et al (1997) used something similar to an air blender, which has stationary angled vanes to mix the air. To achieve a uniform or stratified aerosol concentration distribution in a large wind tunnel, a multiple point feeding system was developed by Heist et al. (2003). Although all the above techniques had been successfully employed, their designs were based on empirical experiences and the approach was a trial and error process. There are no scientific theories or empirical relationships for a novice to follow in designing the mixing system for a new wind tunnel. Secondly, once a large scale wind tunnel has been built, it will be not only difficult but also expensive and time consuming to modify or rebuild it if it does not function well.

Therefore, designers face two challenges: they need experience for designing a wind tunnel and they must make sure that the wind tunnel will function well before it is built. Small scale testing provides an approach to address these challenges. It costs much less money, labor and time to build, disassemble and modify a small-scale tunnel rather than the full-scale one. The performance of the small-scale wind tunnel can also predict the performance of the full-scale wind tunnel.

In this study, a small wind tunnel was built to be 1/5 of the size of the full wind tunnel. Its mixing performance and air velocity profile were evaluated. Different configurations of the tunnel were tested to find the design that best satisfies the USEPA's requirements.

Preliminary Design Consideration

The configuration of a wind tunnel is constrained by its location. Different wind tunnels will have different configurations. In our case, the full-scale wind tunnel will be located on an elevated platform. The fan will be installed on the first floor to minimize the vibration effect. The working area of the cross section is the primary parameter in designing the wind tunnel. In general, the larger the cross sectional area, the longer the wind tunnel must be in order to achieve the desired uniformity of the air velocity. The USEPA requires the horizontal dimension of the sampling zone to be no less than 1.2 times the width of the test sampler and a vertical dimension no less than 25 cm. A cross sectional area of 1.0 m^2 should satisfy our future research requirements. Circular ducts are preferred over rectangular ducts to achieve the uniformity of the aerosol cloud and air velocity (Han, 2003). However, the selection of plywood as the building material limits the shape of the cross sectional area to be rectangular. The cross sectional area was chosen to be a square of 1 m x 1 m. For simplicity, the hydraulic diameter of the duct is defined as one duct diameter (1D) and will be used as the unit throughout the paper.

Air mixing is the most difficult part to design in the whole wind tunnel. Due to the limited space, the air mixer used must provide effective mixing in a short distance. The Aerosol Science Laboratory at Texas A&M University has conducted detailed study of air mixers (Anand et al., 2003) such as air blenders, elbows, Generic Tee Plenum Systems (GTPS), etc. Among all the different types of air mixers, the GTPS has been explored most extensively. The GTPSs are simply rectangular boxes with a square or round inlet as illustrated in Figure 1. The configurations of the GTPSs allow the creation of large scale eddies for thorough mixing at a low-pressure drop. A double air blender (Figure 2) was developed by Blender Products, Inc and is another effective mixer for short distances. It can reduce concentration gradients and ensure a highly uniform concentration throughout the flow. However, double air blenders tend to retain much more dust compared to the GTPS. Therefore, the GTPS was selected as the main air mixer.

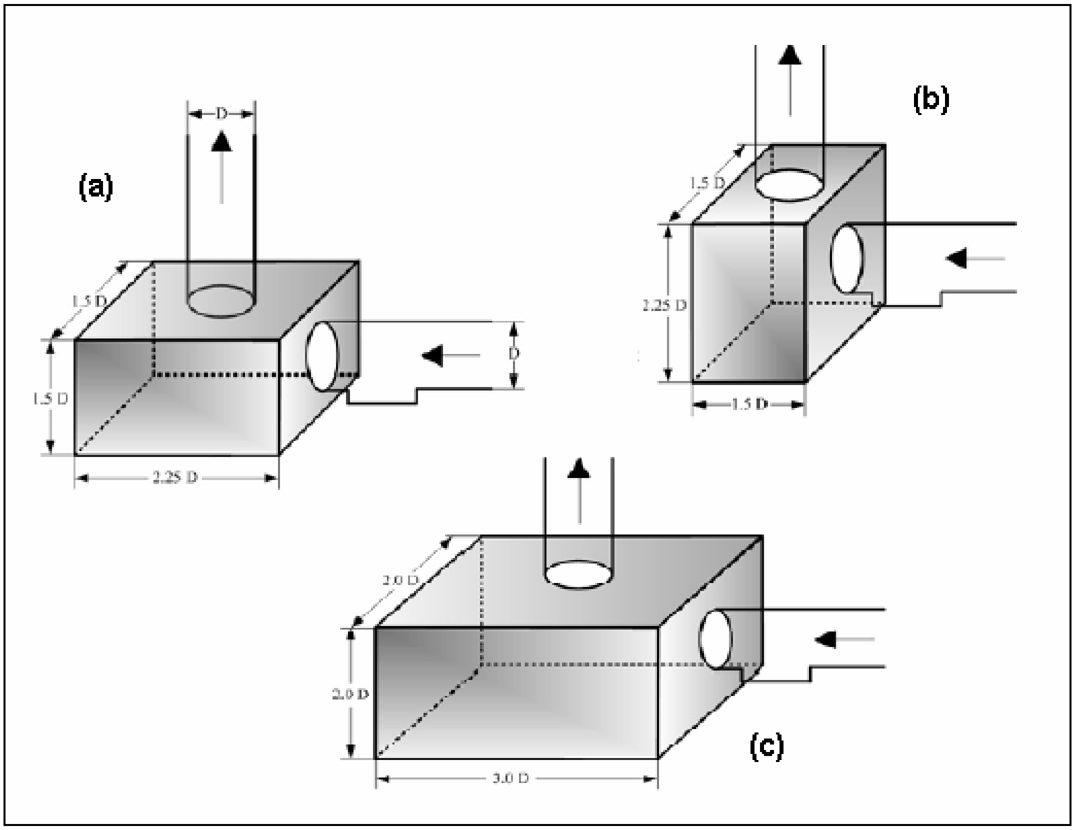


Figure 1. Characteristic dimension of the GTPSs (Han, 2003): (a) small horizontal generic tee plenum system (SHGTPS) (b) small vertical generic tee plenum system (SVGTPS) (c) large horizontal generic tee plenum system (LHGTPS)

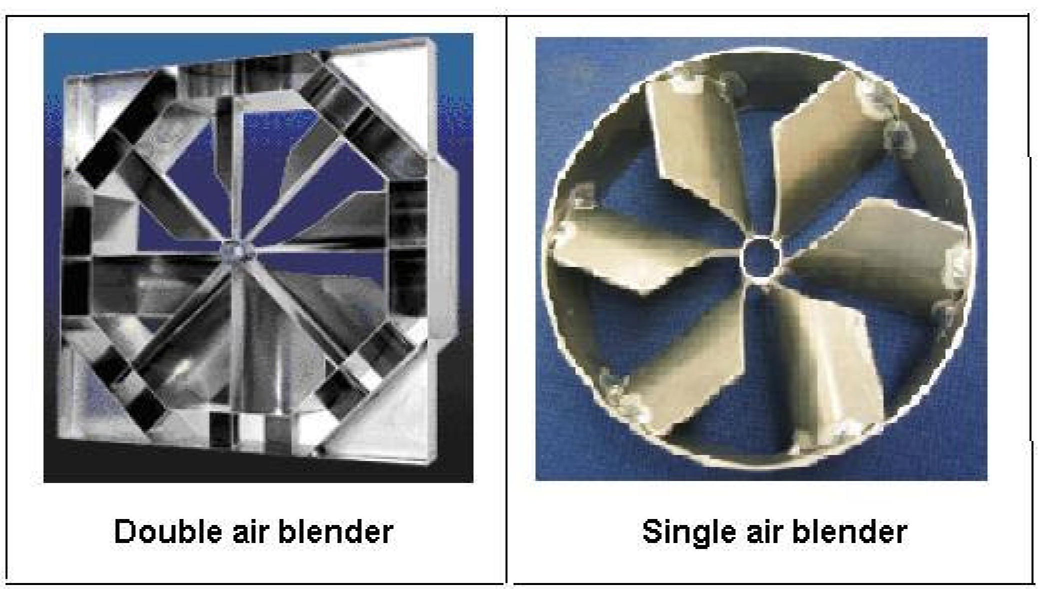


Figure 2. Double square and single round air blenders

Experimental Setup and Procedures

Experimental Setup

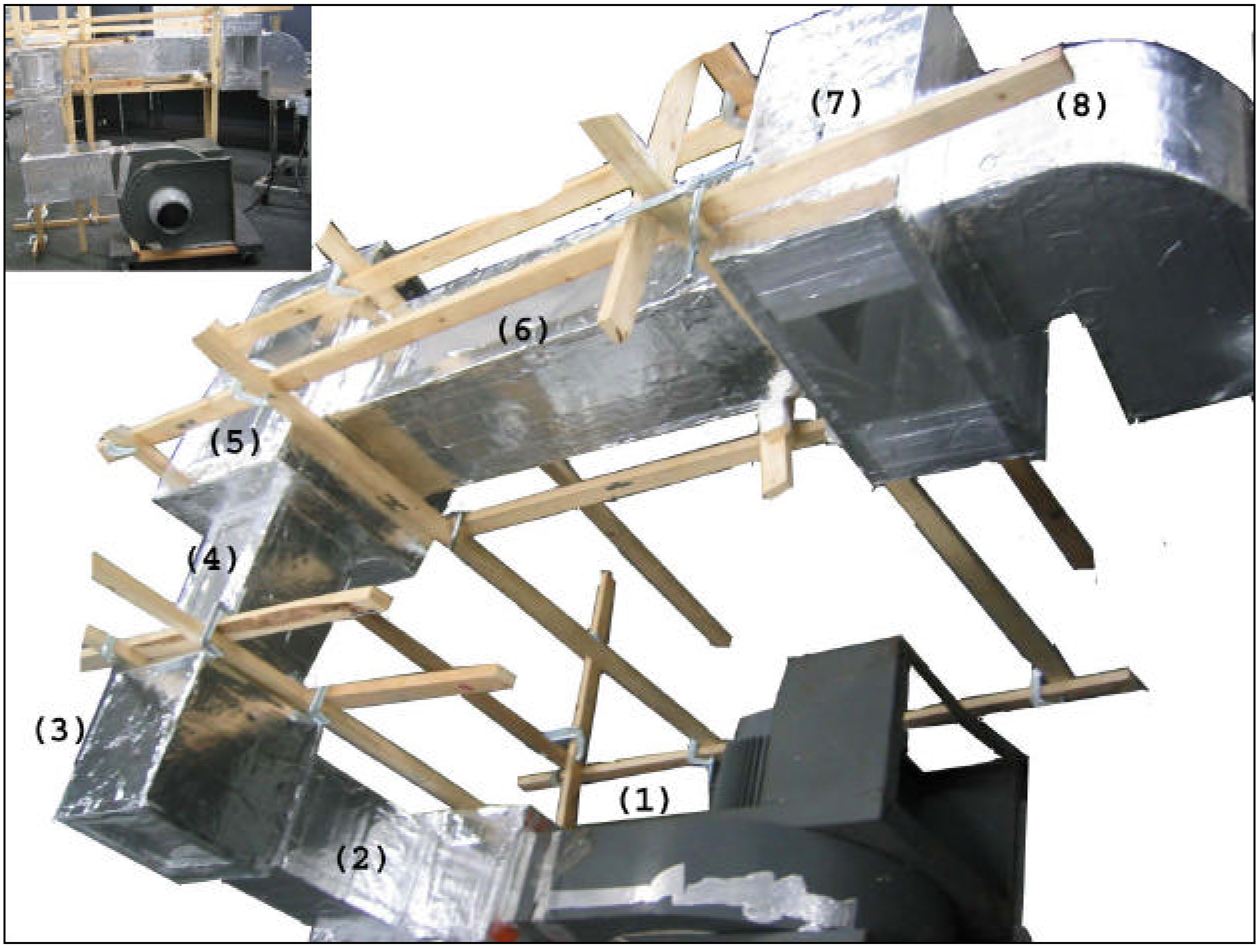


Figure 3. The small-scale wind tunnel. (1) centrifugal fan, (2) inflow duct, (3)rectangular transmission box, (4) feeding duct, (5)GTPS mixing box, (6) flow stabilizing duct, (7) test chamber, (8) 90° elbow

Based on the preliminary considerations, a 1:5 scale wind tunnel was built, as shown in Figure 3. A variable frequency drive was used to regulate the speed of the fan. The fan blew the air through the inflow duct, with dimensions of 15.2 cm x 15.2 cm. The rectangular box functioned as an elbow. Following the rectangular box was the feeding duct, where the trace gas or dust was fed into the main air stream. The air coming out of the mixing box passed through a long duct where the flow was stabilized. At the end of the stabilizing duct was the test chamber whose cross sectional area was expanded to avoid wall effects and make the best use of the sampler test area. The spacious room of the test chamber also provided a convenient space to install the samplers, sensors, and other instruments for the full scale wind tunnel. Air coming out of the test chamber passed through a 90° elbow, which directed the flow out and reduced back flow. This original setup of the wind tunnel also included a 4 cm honeycomb (Figure 4), installed at the inlet of the 90° elbow and a round single air blender (Figure 2) installed at the inlet of the rectangular box. The honeycomb facilitated uniform laminar flow in the test chamber. The round single air blender eliminated any effects from the orientation of the fan.

The small-scale wind tunnel was made from foam insulation boards with aluminum film on one side. Components of the small scale wind tunnel were bonded together and sealed with plastic tape. The whole wind tunnel was strengthened with foil tape on both the inside and outside surfaces.

Experimental Procedure

The wind speeds used for the small-scale wind tunnel were 2 km/h, 8 km/h, and 24 km/h. The first set of experiments was to test the mixing performance of the GTPS since it is always easier to achieve uniform velocity profiles than to achieve good mixing. The original configuration as described above was used. The trace gas (SF_6) was released into the main air stream at the center of the feeding duct. The sampling location was in the middle of the test chamber, 4.625 duct diameters downstream of the GTPS mixing box. The cross sectional area of 20 cm x 20 cm used for sampling was evenly divided into 16 grids. Air samples were extracted with 60 mL hypodermic syringes at the center point of each grid. The SF_6 concentration was measured by an electron capture gas chromatograph tracer gas monitor (AUTOTRAC Model 101, Lagus Applied Technology, San Diego, CA) which has a precision of $\pm$4%. Duplicate sets of samples were collected for each wind speed. The average concentration from the two sets was used to represent the concentration at each point. The coefficient of variance (COV) and the maximum deviations from the mean were used to quantify the mixing efficiency. The COV is defined as:

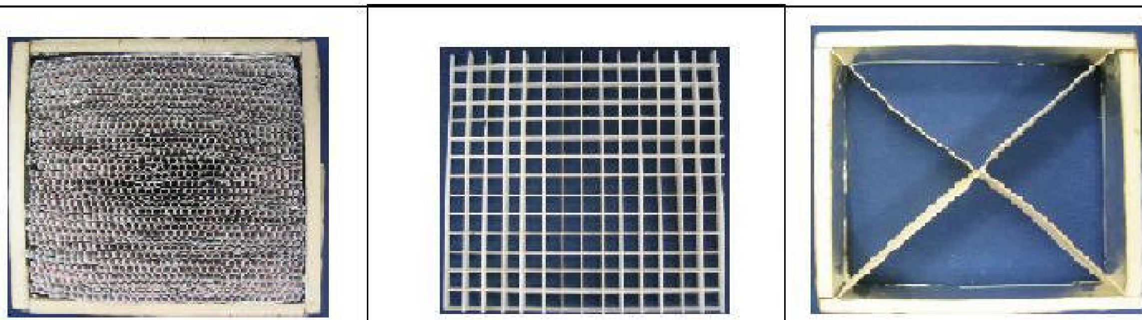
$$COV = \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}}{\bar{x}} \qquad (1)$$

where N is the number of points in the cross sectional area at which measurements are made; x_i is the value of the variable at the i^{th} grid point, and $\bar{x}$ is the mean value of the measurements:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (2)$$

The second set of the experiments was to measure the velocity profiles for the original set up and the modified configurations to find the best configuration to satisfy the USEPA's test requirements. To measure the velocity, the cross sectional area used for sampling was evenly divided into 25 grids and the velocity was measured at the center point of each grid by VELOCICALC Air Velocity (TSI Model 8355, TSI Incorporated, St. Paul, MN) which has an accuracy of ± 2% of the measured values. Three or more continuous reading were recorded and averaged to obtain the representative velocity for each point.

Different air straighteners were tried inside the stabilizing duct, including a honeycomb, screen and X-shaped cross. The honeycomb was used to straighten the air flow and it was effective in removing swirl. The screen was used to reduce the magnitude of turbulence. The X-shaped cross was used to break the large swirls in the flow. The honeycomb, the screen and the X-shaped cross, used in the study, were made of straws, plastic light cover and hard board, respectively as shown in Figure 4.



(a) Honeycomb | (b) screen | (c) X shaped cross

Figure 4. The air conditioners used in the small scale testing

Results and Discussions

Mixing Performance

The maximum deviation from the mean was only 4 percent for the original setup. The COV was less than 2.7 percent for the 16 points at 4.625 duct diameters downstream of the GTPS. Han (2003) conducted similar measurements with a similar setup and got a COV of 6 percent at 4 duct diameters downstream of the GTPS. The reasons why our setup gave better mixing are complex. The inlet cross sectional area of the GTPS is only 0.75 of Han's, which may have produced more turbulence. The rectangular box and the single air blender used at the upstream of the GTPS produced some swirling. This swirling helped mix the trace gas in the feeding duct before entering the GTPS and may have also helped improve the performance of the GTPS. More detailed experiments and numerical simulation is needed in the future to investigate the causes for the improved mixing.

The temporal variation of the concentration profile was tested by sampling continuously 16 times at the same point. The COV and the maximum deviation were found to be 2 percent and 4 percent, respectively, indicating that the concentration profile was very stable with the time. In a comparative test, the trace gas was released at the outlet of the GTPS box. The concentration profile was found to have a COV of 243 percent and a maximum deviation of 938 percent from the mean, indicating that the effective mixing came from the GTPS.

Table 2. The COV and maximum deviation from the mean for the 16 points in the cross sectional area, 4.625 duct downwind of the GTPS mixing box

	2 km/h	*8 km/h*	*24 km/h*
Coefficient of Variance	2.5%	2.2%	2.7%
Maximum deviation from the mean	7%	5%	5%

The results of trace gas tests at three velocities showed that the performance was not affected by the velocity (Table 2). Therefore, the mixing in the full-scale tunnel is expected to be as good as the mixing in the small scale testing. This study did not include any dust-mixing tests since the COV for the trace gas and the dusts concentration was found to be almost the same for the GTPS in numerous, previous studies carried out by Han (2003).

Velocity Profile

The velocity profile for the original setup was measured at 8 km/h. The COV at 4.625 duct diameters downstream of the GTPS was 9 percent, close to Han's experimental measurement of 7.2 percent and numerical simulation of 8.2 percent at 4 duct diameters (2003). However, the maximum deviation from the mean was found to be 20 percent, exceeding the EPA requirement of less than 10%.

A more careful study of the distribution of the velocity indicated that the downstream velocity was always higher on the side that was away from the inlet of the GTPS than on the side that was close to the inlet of the GTPS. Putting some cotton string in the air stream, we were able to observe the airflow in the wind tunnel. Most of the flow coming from the middle part of the inlet of the GTPS entered the side of the stabilization duct closest to the inlet of the GTPS. Different configurations were tried to improve the uniformity of the velocity distribution and the testing results were summarized in Table 3.

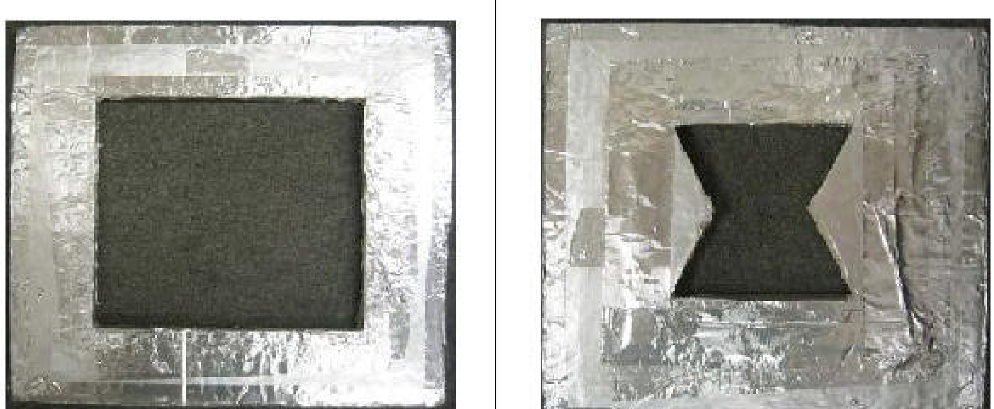
The honeycomb, X-shaped cross and screen were placed downstream of the GTPS. Neither of them changed the velocity stratification. Enlarging the inlet of the GTPS also did not improve the velocity profile. For all the experiments, the velocities in one side of the cross section working area were larger than the velocities on the other side.

Two approaches have been successfully applied to break the stratification of the GTPS. In the first approach, the inlet of the GTPS was reshaped as shown Figure 5. The middle area was narrowed to force more air to go to the top or bottom. The new configuration with the special shaped inlet and a honeycomb at 5.4 duct diameters downstream of the GTPS reduced the maximum deviation from the mean to 11 percent at 5.56 duct diameters downstream of the GTPS for all the three speeds. Shifting the inlet 2 cm away from the center reduced the maximum deviation further to 10 percent.

The double air blender, whose main function is mixing, can act as an air straightener. A square double air blender 20 cm wide (Blender Products, Inc. Denver, USA) was installed at the outlet of the GTPS. With this double air blender and a honeycomb at 5.4 duct diameters downstream of the GTPS, the maximum deviation of the velocity in the whole working area was reduced to less than 10 percent at 5.56 diameters downstream of the GTPS for all the three speeds. Either changing the inlet shape or installing the double air blender, together with a honeycomb, reduced the velocity stratification. However, installing a honeycomb directly upstream of the sampling area will create some sampling problems since solid dusts tend to accumulate on the air conditioners and cause an error if the airflow blows them off to the samplers. In another experiment, the honeycomb upstream of the working area was removed and only a double air blender was installed in the stabilization duct. The maximum deviation from the mean was found to be 18 and 7 percent for the whole test section area and the center area of 0.2 m x 0.16 m, respectively. No additional trace gas mixing tests were conducted on the new configurations since the same strong turbulence was observed inside of the GTPS.

Table 3. The maximum deviation from the mean for the 25 points in the whole cross section downwind of the GTPS mixing box

Configurations	*Distance downwind of GTPS*	*2 km/h*	*8 km/h*	*24 km/h*
Original set up	*4.625 D*	-	20%	-
Enlarge dust input duct size to 8''	*4.625 D*	-	19%	-
Add honeycomb 1D upstream of test section	*5.56 D*	-	18%	-
Add X shaped cross at 0D and honeycomb 1D upstream of test section	*5.56D*	-	14%	-
Add X shaped cross at 4D and honeycomb 1D upstream of test section	*5.56 D*	-	18%	-
Centered special shape GTPS box inlet with honeycomb 1D upstream of test section	*5.56 D*	11%	11%	12%
Move the special inlet away from the center with honeycomb 1D upstream of test section	*5.56 D*	***10%***	***10%***	***10%***
Double air blender at the outlet of GTPS; honeycomb 1D upstream of test section	*5.56D*	***10%***	***8%***	***7%***
Double air blender at the outlet of GTPS	*5.56D*	18%	13%	19%



(a) original GTPS inlet **(b) special shaped GTSPS inlet**

Figure 5, The special shape of the inlet of the GTPS mixing box.

Another possible configuration of the wind tunnel is to replace the GTPS with a 90º elbow and use a double air blender as the main mixer. However, the velocity and trace gas COV of a 90º elbow is much higher than the GTPS as found by Han (2003). In other words, the GTPS, which can function as an elbow, provides more efficient mixing and more uniform flow than an elbow. Compared to the 90º elbow, the GTPS is also cheaper and easier to make.

Conclusion and Discussion

In conclusion,

- The GTPS mixed the trace gas very well in the small scale tunnel
- The X-shaped cross, honeycomb and screens reduced turbulence, but did not break the air flow stratification of the GTPS
- Changing the inlet shape of the GTPS together with an air straightener at 1D upstream of the sampling location improved the velocity uniformity for the whole cross sectional area
- Adding a square double air blender at the outlet of the GTPS and a air straightener at 1D upstream of the sampling location resulted in acceptable velocity uniformity for the whole cross sectional area
- Adding a square double air blender at the outlet of the GTPS without any honeycomb upstream of the sampling location achieved uniform air flow for 80 percent of the cross sectional area

This study showed that the mixing efficiency of the GTPS did not increase when the velocity increased from 2 to 24 km/h in the small-scale tunnel. The Reynolds number did not seem to have any effect on the mixing efficiency. However, if the wind speed is too low or the GTPS is too big, it is possible that insufficient swirl will be formed and there will be limited mixing in the GTPS. If the ratio of the inlet velocity to the outlet hydraulic diameter is defined as the mixing factor, it is anticipated that the mixing efficiency will be related to the mixing factor. This relationship needs to be qualified in future researches to explore the applicability of the GTPS further.

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