Gas sampling efficiencies and aerodynamic characteristics of a laboratory wind tunnel for odour measurement

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Abstract

The rate of odour emission depends on meteorological factors, such as wind speed, humidity and temperature, but no wind tunnels control these factors adequately. A novel laboratory wind tunnel was developed that can control airflow rate. The gas recovery efficiency of the tunnel was evaluated and the aerodynamic characteristics were then examined to further assess its performance. Gas recovery efficiencies ranged from 62 to 107 % with an average of 81 %. The optimal performance of the tunnel (gas recovery efficiency of 89 %) occurred at an airflow rate and CO supply rate of 1.68 m³ min⁻¹ and 10.0 litre min⁻¹, respectively. The vertical and cross-sectional wind speed profiles exhibited a substantial degree of non-uniformity. The airflow was turbulent, although Reynolds numbers were low indicating it to be close to laminar. The non-uniform wind speed profiles and CO concentration profiles illustrate the difficulty in obtaining representative samples from which to calculate...
emission rates. Further work is required to improve aerodynamic characteristics and hence performance of the tunnel.

1. Introduction

One of the main problems in monitoring environmental odours lies in the air sampling method. There are two different methods for collecting air samples from point sources or area sources of odour, namely flux chambers and wind tunnels.

The isolation flux chamber method was developed by the USEPA in 1983 (Klenbusch, 1986) and has been used to measure ammonia emissions from dilute pig slurries (Misselbrook et al., 2004), toxic gases from hazardous waste dumps (Clark et al., 1988), volatile gases from land surface (Klenbusch, 1986), and emissions of nitrous oxide from farmland (Denmead, 1979).

Several factors affect the rate of emissions as sampled by a flux chamber (Smith & Watts, 1994a), including: the pressure inside the chamber relative to that outside; the relatively small area of emitting surface enclosed by the chamber; the suppression of the turbulent transport mechanism which, under ambient conditions, transports the gases away from the emitting surface; the imperfect mixing of the emissions with the sweep air; and modification of the physical environment. The measured emission rate depends particularly on the pressure deficit (or surplus) in the chamber. A deficit of 1.33 Kilopascal (kPa) resulted in a twelve-fold increase in the emission rate (Denmead, 1979). Complete mixing only occurred at 2 to 9.5 cm above the air and water interface. This stratification depends on the temperature of the carrier gas, the
surface temperature and the ambient air temperature. Variations in the thickness of the
stratification layer under different sampling conditions could significantly affect the
repeatability and reproducibility of the results (Gholson et al., 1989).

Generally, the flux chamber records much lower emission rates than either wind
tunnel techniques, micro-met measurements, or modelling (Smith & Dalton, 1999).
Under field conditions, odour emission rates measured with flux chambers and wind
tunnel differ by up to 300 times in some cases (Jiang & Kaye, 1996).

Wind tunnels are portable, open-bottomed enclosures that are placed over the
emitting surface. Ambient or filtered air is drawn or blown through the tunnel in a
way that simulates the convective mixing and transport process present above the
emitting surface (Watts, 1999).

Wind tunnels have been used to estimate ammonia emissions from dairy
collecting yards (Misselbrook et al., 1998), arable land (Loubet et al., 1999b; Genermont & Cellier, 1997), as well as estimating odour emissions from piggeries
(Smith & Dalton, 1999), feedlots (Smith & Watts, 1994b; Watts et al., 1994), poultry
manure (Jiang & Sands, 2000), and anaerobic piggery ponds (Galvin et al., 2002).

Variations in tunnel geometry include differences in the material used in
constructing the tunnel, the length/width ratio, the surface area sampled and the height.
Consequently, there are substantial effects on the exchange coefficients over the
emitting surface. A further complication is the variation in wind speed from one
device to another (Smith & Watts, 1994a).
Smith and Watts (1994b) showed that odour emission rates measured from cattle feedlot were strongly correlated with wind tunnel size. The larger wind tunnel consistently gave emission rates 20% lower than the smaller tunnel. The different wind velocity profiles were suggested as a possible reason for that discrepancy (Watts, 1999).

As it is impossible for natural ground-level wind conditions to be duplicated inside a small wind tunnel, current wind tunnels are only designed to create an environment where the boundary layer is well developed and convective mass transfer occurs. In addition, although the odour emission rate is known to depend on meteorological factors such as wind speed, humidity and temperature (Harper et al., 1983; Smith & Watts, 1994a: Smith & Watts, 1994b), current wind tunnel systems are not able to adequately control these factors.

The aerodynamic performance of a wind tunnel is considered a critical parameter (Jiang & Kaye, 2001). The basic hypothesis for a wind tunnel is that the airflow is completely mixed downwind of the emission chamber of the tunnel. However, the wind profile results from conventional type wind tunnels show strong crosswind and vertical gradients, highlighting the need for a careful analysis of the turbulence the inside the tunnel (Van Belois & Anzion, 1992). Loubet et al. (1999a) evaluated the wind tunnel that was used for estimating ammonia volatilisation from land by Lockyer (1984). They showed that the vertical profiles of wind velocity and gas concentration were non-uniform in the measurement section of the tunnel. The airflow was far from being completely mixed leading to a recovery rate ranging from 77 to
Therefore, Loubet et al. (1999a) suggested that the design of the sampling system may be of great importance in determining the average concentration downwind of the emitting area for a tunnel exhibiting strong vertical gradients.

Baldo (2000) established a wind speed profile map over the emission section for the wind tunnel of the University of New South Wales (Jiang et al., 1995) and the Lockyer hood (Lockyer, 1984). Baldo (2000) indicated that many parameters affect the wind speed profile in the tunnels, including surface type, tunnel wind speed, entrance characteristics, wind tunnel shape and modifications to the tunnel geometry such as vanes and baffles.

A novel laboratory wind tunnel that can control airflow rate was developed to measure the odour emissions under conditions similar to ambient conditions. The wind tunnel was evaluated in terms of the gas recovery efficiency, and the aerodynamics of the airflow inside the tunnel to further improve its performance. Particular attention has been given to the effect of experimental variables such as airflow rate and tracer gas, i.e. Carbon Monoxide, supply rates on the aerodynamics and the gas recovery efficiency rates of the tunnel. It is revealed that the wind tunnel increases the precision of estimates of odour emission rate but needs to be calibrated to compensate for the error caused by different airflow rates and odour emission rates.
2. Materials and methods

2.1. Description of the wind tunnel system

A schematic diagram of the wind tunnel is shown in Fig 1. The wind tunnel covers a horizontal area of 0.25 m$^2$ (0.5 m long by 0.5 m wide), and has a square cross-section. Air is drawn into the tunnel by a variable speed axial-type vent fan, SPEEDLOCK™ AF-300/304 S/S (Eximo® Ltd., Sydney, Australia), connected to the upper part of wind tunnel. The TECO-Westinghouse® variable controller (TECO Australia Pty Ltd, Sydney, Australia) was used as the fan speed controller.

A flow establishment / straightening section is placed upwind of the emission section. A tapered mixing section provides mixing of the emitted gases. There is an air sampling port downstream of the mixing section. The fan can produce wind speeds up to 0.5 m s$^{-1}$ or flow rates up to 1.64 m$^3$ min$^{-1}$ in the emission section. The wind tunnel and all accessories were manufactured using SS 316 food-grade stainless steel.

2.2. Sampling locations in the tunnel

As the wind tunnel has the shape of a rectangular duct, the locations of points for wind speed sampling were selected by the standard method of the Australian Standards 4323.1 (Australian Standard 4323.1: Stationary source emission, 1995). In total, there are 25 sampling points at a cross section midway along the emission section of the tunnel. The vertical and lateral distances to the sampling points are presented in Table 1.
For the initial measurements of gas recovery efficiency, samples were collected using a one point sampling port installed at the downstream end of the mixing section of the tunnel. The measured sample recovery efficiencies ranged between 20.0 % and 81.3 %. Subsequently, a modified sampling port with four branches and five sampling holes per branch was installed in the wind tunnel. The 20 sampling points were spaced quadratically across the sampling port. According to numerical simulations carried out by Loubet et al. (1999a), this type of sampling port showed a theoretical sample recovery efficiency of 100.4 %.

2.3. Experimental design

Three experiments were undertaken:

Experiment 1. The effect of sampling port design on the gas recovery efficiency was identified in experiment 1. Two different types of sampling ports were tested for their effect on gas recovery efficiency. Initially, a simple one-point sampling port was installed centrally at the end of the mixing section and evaluated. Later, a new sampling port with four branches and five quadratically spaced sampling holes per branch (Loubet et al. 1999a), was installed in the tunnel and evaluated.

Experiment 2. The effect of airflow rate and CO supply rate on the gas recovery efficiency of the tunnel was determined. Five different airflow rates, ranging from 0.07 to 1.69 m$^3$ min$^{-1}$, were used. The gas supply rates were 2.5, 5.0, 7.5 and 10.0 litre min$^{-1}$. 
Experiment 3. Aerodynamic characteristics of the tunnel including wind speed profile, turbulent intensity, and gas concentration profile, were investigated at five different airflow rate, ranging from 0.07 to 1.69 m$^3$ min$^{-1}$ over two different types of surface. Two different types of surface, a solid surface (foam mattress) with different roughness heights between 5 and 25 mm and a liquid surface (liquid piggery effluent) were placed in the emissions section of the tunnel.

2.4. Measurements

2.4.1. Temperature and relative humidity

Temperature and relative humidity were measured simultaneously at the inlet and outlet using the HUMITTER$^{\text{TM}}$ 50U/50Y(X) integrated humidity and temperature transmitter (Vaisala$^{\text{R}}$ Ltd., Melbourne, Australia). Remote I/O module ADAMS 4000$^{\text{TM}}$, was used to collect these data (Advantech$^{\text{R}}$ Australia Ltd., Sydney, Australia). Dedicated operating software was developed for real-time monitoring of the tunnel and data logging using Labview$^{\text{TM}}$ Ver. 5.1 (National Instrument$^{\text{R}}$, USA). Each measurement was made over a 900 s period at a sample rate of 20 Hz.

2.4.2. Carbon monoxide concentration

Pure carbon monoxide (CO) gas was used as a tracer gas for the gas recovery efficiency experiment. The CO gas was introduced into the tunnel through perforated tubes. CO concentration was 200 ppm (BOC$^{\text{R}}$ Australia, Brisbane, Australia). Four tubes were laid out under the emission section of the tunnel in parallel rows. Each tube had 50 tiny holes per metre to provide homogeneous gas emissions to the tunnel.
A visual flowmeter (Cole-Parmer®, USA) and a needle valve (Swagelok® Ltd., Australia) were used to control the CO supply rate.

The CO concentration was measured with the 300E gas filter correlation CO analyser™ (Teledyne Instruments®, USA) at a frequency of 10 Hz. Air was continuously sampled at the sampling port and drawn to the analyser through polytetrafluoroethylene (PTFE) tubes with 4 mm inner diameter (Swagelok® Ltd., Australia). The analyser was calibrated regularly with two reference standard CO gases (BOC® Australia, Brisbane, Australia) at 206 and 1000 ppm. The detection limit of the CO analyser was 0.04 ppm. Linearity was better than 1 % full scale for CO concentrations greater than 10 ppm, and better than 0.2 ppm for lower concentrations. The precision was 0.5 % of the value read.

2.4.3. Normalisation of CO concentration

To get normalised gas concentration, the mean volumetric concentration increase in a section of the tunnel $\overline{C}_{inc}$ is calculated as the ratio of the CO volumetric flow injected into the tubes $Q_{CO}$, to the volumetric airflow in the tunnel $Q$ (modified from Loubet et al., 1999a):

$$\overline{C}_{inc} = \frac{Q_{CO}}{Q}$$

The normalized concentration is then defined as the ratio of the concentration at a given position $C_Z$ minus the background concentration $C_B$ to the mean concentration increase $\overline{C}_{inc}$ in the same cross-section:
2.4.4. Gas recovery efficiency rate

The recovery rate of the tunnel ($\alpha$) was calculated using the equation (3) (modified from Loubet et al., 1999a).

\[ \alpha = \left( \frac{\bar{Q} \bar{C}_m}{A_{exp} \Phi_{exp}} \right) \]

where $\bar{Q}$ is the mean volumetric airflow rate through the tunnel in m$^3$ s$^{-1}$; $A_{exp}$ is the experimental area covered by the tunnel in m$^2$; $\bar{C}_m$ is the measured average concentration in the measurement section in kg m$^{-3}$; $\Phi_{exp}$ is the CO emission rate in the emission section in kg m$^{-2}$ s$^{-1}$.

2.4.5. Wind speed

The wind speed was measured with a Velocica_tm velocity meter (TSI\textsuperscript{®} Incorporated, USA). Absolute accuracy of the wind speed meter was 1 % of full-scale, which corresponded to 0.01 m s$^{-1}$. The probe was located as described in section 2.2 for the vertical wind speed profiles and cross-sectional wind speed profiles. For the gas recovery efficiency trials, the probe was placed in the middle of the emission section of the tunnel as a reference. As the wind speed meter gives result in standard temperature and pressure condition, the wind speed was corrected by a factor $T / 294.55$, where $T$ is the ambient temperature in K.
2.4.6. Standardisation of airflow rate

The volumetric airflow rate at standard conditions (0 °C and 101.3 kPa) was then calculated in accordance with ISO 10780 using equation (4) (modified from AS4323.1, 1995)

\[
\overline{Q}_{r,0} = \overline{Q} \cdot \frac{(273 + 0)}{(273 + T_t)} \frac{P_s}{101.3}
\]  

(4)

where \(\overline{Q}_{r,0}\) is the volumetric airflow rate at standard conditions (0 °C and 101.3 kPa), \(\overline{Q}\) is the mean volumetric airflow rate through the tunnel, m³ s⁻¹; \(P_s\) is the absolute pressure in the tunnel, kPa; \(\overline{Q}\) is the mean volumetric airflow rate through the tunnel, m³ s⁻¹; and \(T_t\) is the tunnel temperature, °C.

2.4.7. Turbulence Intensity

The turbulence intensity, \(I\) is defined by three variables: the turbulent component of the wind speed \(v'\), the mean wind speed in the profile \(\overline{V}\), and the maximum wind speed in the profile \(V_{\text{max}}\), where:

\[
v' = \overline{V} - V
\]  

(5)

\[
I = \frac{\sqrt{v'^2}}{V_{\text{max}}}
\]  

(6)
3. Results and discussion

3.1. Gas recovery efficiency of the wind tunnel

3.1.1 Effect of sampling port design on the gas recovery efficiency

The results of experiment 1 regarding the sampling port design are summarised in Table 2. When the CO gas was supplied at a rate of 5.0 litre min$^{-1}$, the sample recovery efficiency using the one point sampling port ranged from 20% to 81%. The mean ± standard deviation (std) recovery efficiency was 49 ± 29%. In contrast, the sampling point with four branches and five quadratically spaced sampling holes per branch produced a mean ± std recovery efficiency of 71 ± 11%. The range of recovery efficiencies was 64 to 90%. This improvement is solely due to the improved sampling port. Similarly, Loubet et al. (1999a) reported ‘simulated’ recovery efficiencies of a one point and a 20 point sampling port (with a linear distribution) of 61% and 89% respectively, and of 100.4% with a quadratic distribution. For the linear distribution of sampling points, the number of sampling points per unit area will decrease with distance to the centre of the duct, whereas in the case of a quadratic distribution, it remains constant.

3.1.2 Effect of airflow rate and gas supply rate on gas recovery efficiency

The results of experiment 2 are presented in Fig 2. The results reveal gas recovery efficiencies for individual tests ranging from 62 to 107%, while the average result for the entire data set was 81%.
Optimal performance, that is, consistently high gas recovery efficiencies, was 89 ± 4% at an airflow rate of 1.68 m$^3$ min$^{-1}$. The recovery efficiency at this optimal condition is similar to or better than efficiencies reported in other studies using different wind tunnel systems. Other researchers reported recovery efficiencies in a range from 70% to 103% under varying tunnel geometry and operating conditions (Wang et al., 2001; Loubet et al., 1999b; Reitz et al., 1997; van der Weerden et al., 1996; Mannheim et al., 1994).

At the airflow rate of 0.89 m$^3$ min$^{-1}$, the tunnel showed the highest averaged gas recovery efficiency rate of 95 ± 16%. However, this result was leveraged by overestimated recovery efficiencies of 107% and 104%. It also included high variability as shown by the standard deviation value.

Gas recovery efficiencies at CO gas supply rates of 2.5, 5.0, 7.5 and 10.0 litre min$^{-1}$ were 80 ± 17%, 71 ± 11%, 81 ± 14% and 92 ± 10% respectively.

The gas recovery efficiencies and hence estimates of emission rates, made from the concentrations measured in the tunnel, are closely related to the uniformity of concentration profiles and the degree of mixing developed inside the tunnel. The results of this study suggest that the wind tunnel will give estimates of the odour emission rate with a significantly improved level of accuracy. However, the wind tunnel needs to be calibrated to compensate for the different recovery efficiencies caused by different airflow rates. To get more reliable and repeatable results,
improvements to the wind tunnel to improve mixing downstream of the emissions section will be required.

3.2. Aerodynamic characteristics of the wind tunnel

3.2.1. Wind speed profiles

The mean vertical profiles of wind speed measured at the centre of the emission section of the tunnel, over the solid surface and over the liquid surface are presented in Fig 3 and Fig 4.

While the airflow rate was increasing, the horizontal wind speed was increasing accordingly. However, the wind speed profiles were not uniform regardless of the airflow rate. For all of the higher airflow rates, there was a pronounced peak in the profile at about 0.1 m above the bottom of the emission section for the solid surface and 0.15 m for the liquid surface. The lowest wind speed was usually recorded at the bottom of the profile, which had a logarithmic shape. Moreover, for any given airflow, the maximum wind speed was higher over the liquid surface than over the solid surface.

Compared with the wind speed profile results reported by Leyris et al. (2000) and Loubet et al. (1999a), both sets of profiles indicated incomplete development of the flow, caused by an insufficient straight length of ducting prior to the emission section.
The contour plot for the cross-sectional wind speed profile over the solid surface is shown in Fig 5, and over the liquid surface in Fig 6. These profiles show a variation in wind speed across the width of the tunnel. In each case, two zones of high wind speed are observed near the centre of each half of the cross section.

One possible explanation for these flow patterns is low wind speed. Compared to conventional wind tunnels operated at $0.1 - 0.5 \text{ m s}^{-1}$, the highest wind speed measured at the emission section of the tunnel was $0.26 \text{ m s}^{-1}$. The height of the emission section is 300mm. Frechen (2003) indicated that, as the wind speed is influenced by the tunnel height, it was possible to increase the sweep wind speed by reducing the tunnel’s height. Besides, low height tunnels are advantageous due to their better behaviour concerning flow pattern and vertical homogeneity. He suggested that heights greater than $0.15 \text{ m}$ should be avoided.

3.2.2. Flow characteristics

Reynolds numbers above $1 \times 10^4$ are associated with turbulent flow. The Reynolds number is defined as:

$$R_e = \frac{LV\rho}{\nu}$$  \hspace{1cm} (7)

where $R_e$ is the Reynolds number; $L$ is the characteristic length of the duct in m; $V$ is the wind speed in the duct of the wind tunnel in m s$^{-1}$; $\rho$ is the density of the air in kg m$^{-3}$; $\nu$ is the dynamic viscosity of the air, kg m$^{-1}$ s$^{-1}$.

The dynamic viscosity of air at 20 °C is about $1.8 \times 10^{-5}$ kg m$^{-1}$ s$^{-1}$. Hence, the Reynolds number was estimated to $1.4 \times 10^4$ in this wind tunnel. Therefore, the
airflow inside the duct is revealed to be turbulent flow. However, this number is lower
than the Reynolds number of between $3 \times 10^4$ and $9 \times 10^4$ presented by Loubet et al.
(1999a) for their wind tunnel. This lower Reynolds number is due mainly to the low
range of wind speeds that were applied in this research.

The turbulence intensity profiles over the solid surface and the liquid surface are
shown as a function of height in Fig 7 and 8, respectively. As with the wind speed
profiles, the vertical profiles of turbulence intensity are not uniform regardless of the
airflow rate and surface type. In fact, the turbulence intensity shows an inverse
relationship with wind speed. The highest intensity is located where wind speed is
lowest, that is, close to the wall of the wind tunnel. The turbulence intensity profiles
are similar in shape to those reported by Loubet et al. (1999a). However, it is
observed that the peak turbulence intensity over the solid surface is higher than for the
liquid surface for the same fan speed.

3.2.3. Gas concentration profiles in the emission section of the tunnel

The vertical CO concentration profiles measured in experiment 3 are presented in
Fig 9. The CO supply rate was 5 litre min$^{-1}$. The trial was done over the solid surface,
and the CO concentration profiles measured within the emission section of the tunnel.

The normalised CO concentration profiles showed the strong asymmetry, typically
seen in the results of dispersion modelling of area source emissions (for example,
Harris et al. (1996). Concentration is a maximum close to the emitting surface,
tapering rapidly with height above the surface. The normalised concentration profiles
were similar in shape for the five different airflow rates. These results are also similar
to the gas concentration profiles within conventional wind tunnels, reported by Loubet et al. (1999a) and Leyris et al. (2000). They indicated that the asymmetry would likely be independent of the wind speed in the tunnel, for a given geometric configuration of the experimental area.

The presence of concentration gradients in the air stream illustrates the difficulty in obtaining a representative sample from which to estimate the odour emission rate. Leyris et al. (2000) suggested that the traditional way to calculate emission rates from wind tunnel samples (equation 3) is not valid because of these concentration gradients.

3.3 Suggestions to improve the performance of the tunnel

Loubet et al. (1999a) proposed three hypotheses are necessary for equation 3 to be valid, viz: the turbulent component of the horizontal wind velocity is assumed to be negligible in the inlet and the measurement section of the tunnel; the wind speed profile is assumed to be constant in the cross-section of the duct; and the concentration gradients in the duct are assumed to be low, so that the average concentration can be estimated accurately from a sampling system with a limited number of sampling points.

However the same result may be achieved more simply by designing the tunnel to ensure adequate mixing of the air stream prior to sampling. The relatively high gas recovery efficiencies presented earlier suggest that a substantial degree of mixing has already been attained.
An issue of perhaps greater importance is the nature of the vertical wind speed profiles in the tunnel and how the emission rates relate to ambient emissions. Jiang and Kaye (2001) designed their tunnel to give a uniform wind speed profile. However, the method commonly used to convert the tunnel emission rate to an equivalent ambient value (Galvin et al., 2004) assumes that the typical ambient logarithmic profiles apply. Open tunnels such as that of Lockyer (1984) would have profiles approximating ambient conditions. The tunnel examined in this study has neither a uniform nor logarithmic profile. Substantial further work is required to: (i) determine the most appropriate profile to apply in the tunnel, and (ii) modify the tunnel to achieve the desired profile.

4. Conclusions

This wind tunnel is expected to be a more precise tool for odour sampling because it has the potential to duplicate natural ground-level wind conditions more effectively than other wind tunnels and with a capability to control airflow rates. Therefore, it will be suitable for more demanding tasks like the measurement of the kinetics of odour emission rates from specific odour sources. Gas recovery efficiencies in the tunnel were consistently high at the higher wind speeds indicating that under these conditions it will give accurate estimates of odour emission rates. Further improvements in the gas recovery efficiency and in the aerodynamic performance of the tunnel are possible.
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**Fig 1. Schematic diagram of the wind tunnel system. It was designed to have a capability to control airflow rates from 0.07 to 1.69 m\(^3\) min\(^{-1}\)**
Fig 2. Sample recovery efficiency rates for different airflow rates and gas supply rates.
Fig 3. Mean vertical profiles of wind speed over the solid surface for several airflow rates: ●, 0.07 m$^3$ min$^{-1}$; ○, 0.28 m$^3$ min$^{-1}$; ▼, 0.89 m$^3$ min$^{-1}$; ▽, 1.41 m$^3$ min$^{-1}$; ■, 1.69 m$^3$ min$^{-1}$ (the error bar represents the value of standard deviation)
Fig 4. Mean vertical profiles of wind speed over the liquid surface for several airflow rates: ●, 0.07 m$^3$ min$^{-1}$; ○, 0.28 m$^3$ min$^{-1}$; ▼, 0.89 m$^3$ min$^{-1}$; ▽, 1.41 m$^3$ min$^{-1}$; ■, 1.69 m$^3$ min$^{-1}$.
Fig 5. Contour map of cross-sectional wind speed over the solid surface at the airflow rate of 1.69 m$^3$ min$^{-1}$. The unit of wind speed is m s$^{-1}$. 
Fig 6. Contour map of cross-sectional wind speed profiles over the liquid surface at the airflow rate of 1.69 m$^3$ min$^{-1}$. The unit of wind speed profiles is m s$^{-1}$.
Fig 7. Turbulence intensity profiles over the solid surface: ●, 0.89 m$^3$ min$^{-1}$; ○, 1.41 m$^3$ min$^{-1}$; ▼, 1.69 m$^3$ min$^{-1}$
Fig 8. Turbulence intensity profiles over the liquid surface: ●, 0.79 m³ min⁻¹; ○, 1.22 m³ min⁻¹; ▼, 1.69 m³ min⁻¹
Fig 9. Normalised CO concentration profiles over the solid surface with a 5 litre min$^{-1}$ CO supply rate: •, 0.12 m$^3$ min$^{-1}$; ○, 0.30 m$^3$ min$^{-1}$; ▼, 0.78 m$^3$ min$^{-1}$; ▽, 1.26 m$^3$ min$^{-1}$; ■, 1.68 m$^3$ min$^{-1}$
Table 1.

Vertical and horizontal distances for wind speed sampling

<table>
<thead>
<tr>
<th>Cross sectional distances, m</th>
<th>Vertical distances, m</th>
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<tr>
<td>0.08</td>
<td>0.05</td>
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<tr>
<td>0.17</td>
<td>0.10</td>
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<tr>
<td>0.25</td>
<td>0.15</td>
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<tr>
<td>0.33</td>
<td>0.20</td>
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<td>0.42</td>
<td>0.25</td>
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</table>
Table 2.

Gas recovery efficiency of the tunnel for one point sampling port (port A) and 20 points four branched sampling port with quadratic distributed holes (port B) with a CO supply rate of 5 litre min$^{-1}$

<table>
<thead>
<tr>
<th>Port design</th>
<th>Airflow rate ($m^3 \text{ min}^{-1}$)</th>
<th>CO concentration (ppm)</th>
<th>Recovery efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Theoretical</td>
<td>Measured</td>
</tr>
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<td>Test 1</td>
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<tr>
<td>A</td>
<td>0.07</td>
<td>14.24</td>
<td>2.85</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>9.30</td>
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<td></td>
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<td>A</td>
<td>0.28</td>
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<td>B</td>
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<tr>
<td>Test 3</td>
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<tr>
<td>A</td>
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