

# TECHNICAL REPORT



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Title:

**EFFICIENCY TESTS OF THE DUST CLEANING  
SYSTEM IN THE CHINBU TUNNEL - SOUTH  
KOREA BASED**

**Light scattering measurement and  
laser particle counting**

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## ABSTRACT :

The Korean road authorities (KHC) have installed an electrostatic precipitator (EP) based cleaning system from CTA International to remove particle fractions from the tunnel air in the Chinbu tunnel - South Korea. The EP cleaning system in the Chinbu tunnel is the first of its kind in South Korea.

Chinbu tunnel has a length of 2317 m and a cross-section area of 63.4 m<sup>2</sup>. The cleaning system is located in a bypass tunnel about 500 m from the outlet of the main course. The cleaning system consists of an inertial filter, dampers, an electrostatic precipitator and an after-filter.

The average efficiency for particles between 0.3 μm and 10 μm has been calculated. These calculations show that the average particle efficiency varies from 93.8 % to 96.9 %.

Light scattering measurements have shown an overall weight efficiency from 82.8 % to 90.4 %. Due to different and varying dust bulk density upstream/downstream the cleaning system, the light scattering measurement however more represent a volume-efficiency than a weight-efficiency.

KEYWORDS :

Road tunnel, dust cleaning system, efficiency testing

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## SUMMARY

The Korean road authorities (KHC) have installed an electrostatic precipitator (EP) based cleaning system from CTA International to remove particle fractions from the tunnel air in the Chinbu tunnel - South Korea. The EP cleaning system in the Chinbu tunnel is the first of its kind in South Korea.

The Chinbu tunnel has a length of 2317 m and a cross-section area of 63.4 m<sup>2</sup>. The cleaning system is located in a bypass tunnel about 500 m from the outlet of the main course. The cleaning system consists of an inertial filter, dampers, an electrostatic precipitator and an after-filter.

The cleaning system is equipped with a fully automated washing system. A water treatment system separates particulate fractions and detergents from the wash water, and returns purified water to a clean water tank for recycling.

In default of a suitable test standard for verifying the efficiency of full-scale cleaning systems installed in road tunnels, elements from the test standards ASHRAE 52.1 and EUROVENT 4/9 have been used. It has been agreed that the weight efficiency test in the Chinbu tunnel is to be carried out by using two real-time light scattering aerosol monitors in combination with gravimetric measurements of membrane filters. The particle efficiency test is to be carried out by use of the successively fractional efficiency method. To avoid long transfer lines, the efficiency tests were executed using one laser particle counter that was manually moved between the upstream and downstream measuring sections.

The efficiency tests have been repeated three times as prescribed in the contract between CTA International and Doosan Construction and Engineering. The first test was carried out on Tuesday 1999-10-19. During the tests, the climate parameters and traffic situation have been recorded. Also the primary voltage and high voltage supply to the EP cells have been recorded.

Based upon measured particle efficiency for each fraction covered by the particle counter, an average efficiency for particles between 0.3 μm and 10 μm has been calculated. The calculations show that the average particle efficiency varies from 93.8 % to 96.9 %.

Light scattering measurements have shown the overall efficiency to range from 82.8 % to 90.4 %. The lowest efficiency was observed during a period where the thermal fuses protecting the EP power packs caused a voltage dropout. The results presume a dust bulk density of 2.6 g/cm<sup>3</sup> upstream and downstream of the cleaning system.

However, additional tests have shown that the dust density varies widely ( 1 to 3 g/cm<sup>3</sup>) with respect to time and location. Results presented may therefore represent dust volume more than dust weight.

## 1 INTRODUCTION

The Korean road authorities (KHC) have installed an electrostatic precipitator (EP) based cleaning system in the Chinbu tunnel - South Korea. This system is designed to remove particle fractions from the tunnel air. The Chinbu tunnel is part of the Yong Dong Expressway running from the West Coast to the East Coast. The Chinbu tunnel is located 200 km east of Seoul (670 m above sea level) at the inlet of the Mt. Odeasan National Park which has an area of 300 km<sup>2</sup>. In the same area we also find the Yongpyeong Ski Resort. The location of the Chinbu tunnel is marked with a red cross in Figure 1.1 which is a map of South Korea.



Figure 1.1 Map of South Korea (the Chinbu tunnel is marked with a red cross)

The EP cleaning system in the Chinbu tunnel is the first of its kind in South Korea. The main reason for installing the cleaning system is to improve the visibility in the tunnel, and avoid the concentration of road dust and particulate combustion products from vehicles at the inlet of the national park.

## 2 DESCRIPTION OF THE TUNNEL AND AIR CLEANING SYSTEM

The Chinbu tunnel has a length of 2317 m, a cross-section area of 63.4 m<sup>2</sup> and the gradient is 1.84 %. The cleaning system is located in a bypass tunnel about 500 m from the outlet of the main course. The tunnel is designed with one-way traffic and two lanes. Figure 2.1 shows a photo of the tunnel.



Figure 2.1 Chinbu tunnel

Airflow through the main course is caused by the traffic and a set of ceiling mounted axial fans. To make sure that the airflow in the main course is forced through the bypass and the cleaning system, the bypass tunnel is supplied with 2 axial fans with capacity 285 m<sup>3</sup>/s.

The cleaning system consists of an inertial filter, dampers, an electrostatic precipitator and an after-filter. The inertial filter removes the coarse dust and accumulates it in dust-tanks, which are periodically emptied by tank trucks. The filter manufactured by Locer Air-Maze Ltd, has a gross area of 27 m<sup>2</sup>. Air velocity through the filter at nominal airflow is measured at 13.5 m/s.

The electrostatic precipitator removes the fine dust. The fine dust particles pass through a strong electrostatic field where they are electrically charged. In the subsequent collector with interleaved plates, the charged particles accumulate while clean air passes through with a small drop in pressure. At regular intervals, a fully automated washing system flushes the collector plates with detergents and water. The used water is stored in a dirty water tank. A water treatment system separates particulate fractions and detergents from the used water, and returns purified water to a clean water tank for recycling.

The modular designed electrostatic precipitator consists of 132 cells manufactured by CTA International. The cell, including ionizer and collector section is built from stainless steel and aluminium and measures 830x600x600 mm. The cells cover an area of 74 m<sup>2</sup> and have a flow area of 44 m<sup>2</sup>. The cells are supplied with high voltage from 33 power packs.

The after-filter is based on a woven metal filament and is designed to handle re-entrainment of dust collected on the interleaved plates. Once collected on the plates, the dust is not caught once and for all. For instance pressure waves caused by large vehicles or uneven air distribution may cause dust layer to loosen. The after-filter is equipped with a fully automated washing system. The after filter made up from 216 filter-sections and has a flow area of 78 m<sup>2</sup>.

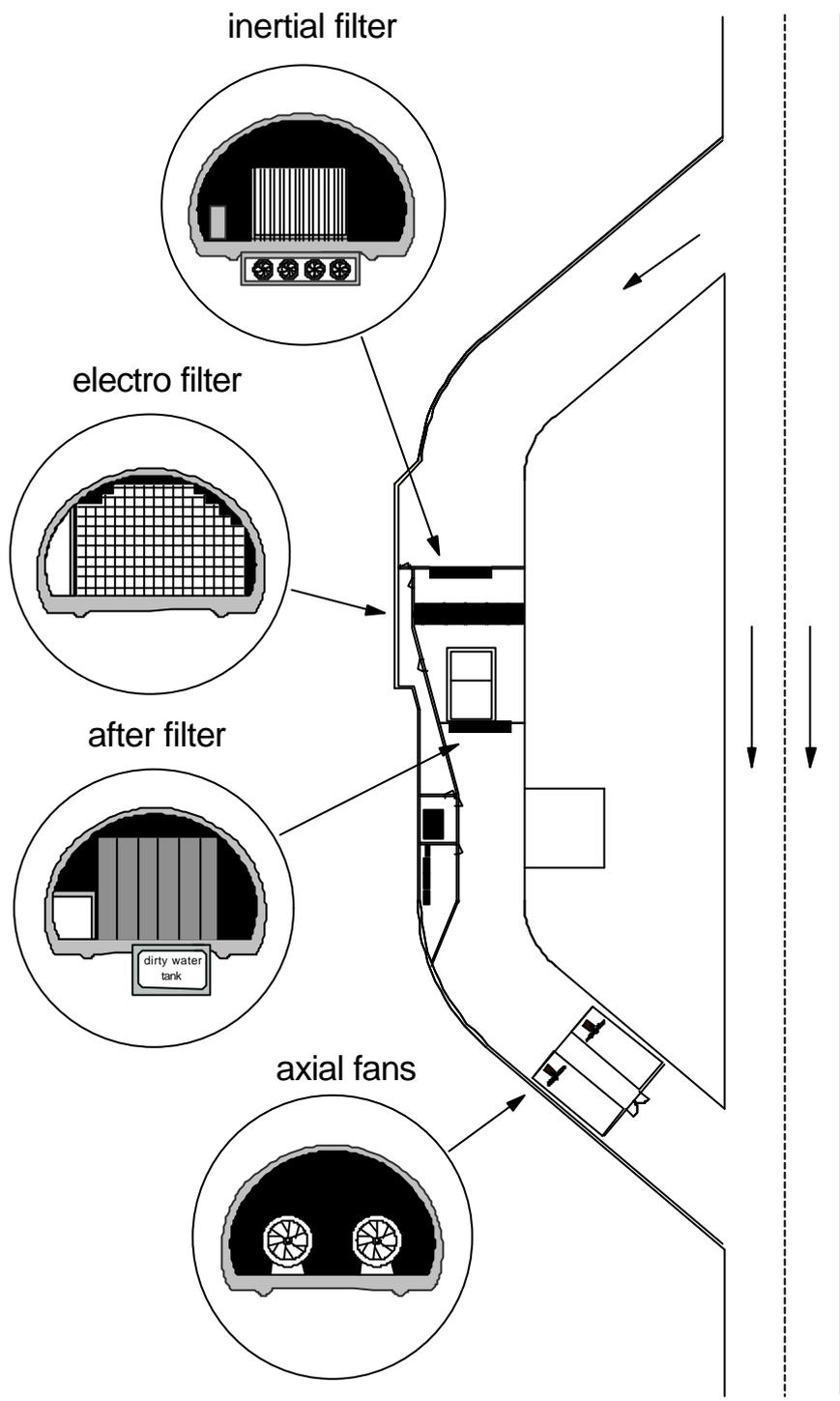


Figure 2.2 Bypass with cleaning system

### 3 DESCRIPTION OF TEST METHODS AND MEASURING PRINCIPLE

#### 3.1 Test standards

The two standards ASHRAE 52.1 (1992) and EUROVENT 4/9 (1992) describe three different test procedures for evaluating the performance of air cleaning devices used in general ventilation for removing particulate matter.

The ASHRAE dust spot efficiency method is based on opacity measurement of test dust collected on dust spot target papers (glassfibre filter) exposed by the dust in the airflow upstream and downstream of the test-cleaning device. The efficiency is found by comparing the light transmission of stains on the paper targets. The dust spot efficiency (E) is calculated by Equation (1):

$$E = 100 * (1 - (S_u/S_d) * (Y_d/Y_u)) [\%] \quad (1)$$

$S_u$  : exposure time of upstream sampler

$S_d$  : exposure time of downstream sampler

$Y_u$  : opacity of upstream filter paper

$Y_d$  : opacity of downstream filter paper

The test method requires ASHRAE test dust and a dust spot opacity meter, isokinetic probes and spot target filters.

The ASHRAE weight arrestance method is identical to the EUROVENT 4/9 weight arrestance and dust holding capacity method. The method gives a measure of the ability of a device to remove ASHRAE dust from the test air. Arrestance is the percentage of the dust captured by the cleaning device. During the test a weighted quantity of test dust is fed upstream of the test device. Dust passing the test device is collected in a pre-weighted HEPA-filter. Filter arrestance (A) is calculated by Equation (2) :

$$A = 100 * (1 - (W_d/W_u)) [\%] \quad (2)$$

$W_d$  : weight of dust collected in the HEPA-filter

$W_u$  : weight of dust fed

The test method requires ASHRAE test dust and a weighing device with high resolution. The recommended dust concentration in the upstream air during the test should be  $71 \text{ mg/m}^3$ . Weight accuracy should be within  $\pm 0.1 \text{ g}$

The EUROVENT 4/9 fractional efficiency method uses a laser particle counter to count particles within specified ranges upstream and downstream of the test device. A given particle size range means all the particles between two specified diameter values. The number of ranges is equipment specific, for instant the laser particle counter MetOne M200L has 6 ranges. (0.3 - 0.5  $\mu\text{m}$ , 0.5 - 1.0  $\mu\text{m}$ , 1.0 - 2.0  $\mu\text{m}$ , 2.0-5.0  $\mu\text{m}$ , 5.0-10  $\mu\text{m}$  and >10  $\mu\text{m}$ ).

The basic expression of the fractional efficiency for a given particle size range is the ratio of the number of particles retained by the filter to the number of particles fed upstream of the filter. The efficiency measurement is done by a series of 12 counts of one minute, conducted

successively upstream and downstream of the test device. Between each count the transfer lines are purged for one minute. The fractional efficiency (E1) for one repetition is calculated by Equation (3)

$$E1 = (1 - (2 * n2 / (N1 + N3))) * 100 [\%] \quad (3)$$

N1 : downstream count at time 1

n2 : upstream count at time 2

N3 : downstream count at time 3

The final efficiency should be equal to the average of E1..E6. As test aerosol, EUROVENT 4/9 recommends DEHS or latex particles.

The test method requires a laser particle counter and three one-way valves to count upstream, downstream and purge. As an alternative one can employ a co-calibrated dual laser system. Additionally, the test method needs an aerosol generator and isokinetic probes.

Both ASHRAE 52 and EUROVENT 4/9 assume that the tests are carried out in a laboratory test rig, that is developed specially for bag air filter efficiency measurements.

### 3.2 Field measurements

Neither ASHRAE 52 nor EUROVENT 4/9 describe methods for carrying out efficiency measurement in the field, and there are no other standards covering such measurements. The ASHRAE and EUROVENT standards are primarily intended to test devices with nominal face dimensions of 610 mm x 610 mm, with face velocity ranging from 0.5 - 2 m/s.

The ASHRAE *dust spot method* requires synthetic dust with 23 % powdered-carbon. The method is not practical for large field installations.

The ASHRAE/ EUROVENT *weight arrestance method* can be modified and adapted for a field study. Dust spot samples taken from selected spots covering sections upstream and downstream the cleaning installation will give us average dust concentration ( $\text{mg/m}^3$ ) in front and behind the installation. The method presumes that the natural occurrence of dust in the air is sufficient for test purpose. Arrestance efficiency is calculated in accordance with Equation (2). The dust concentration may be detected by gravimetric measurements of dust spot target papers, or by using on-line light scattering devices.

Gravimetric measurements using dust spot target papers, involve drying and weighing of target papers before and after they are exposed to air flow samples from the tunnel. Exposure time is related to the dust concentration and sample flow through the target paper. Results from the test are not available before the laboratory weighing has been carried out. If the exposure time has been too short or the sample flow has been too low, the dust quantity on the target papers will be insufficient for accurate weighing. The test therefore has to be rejected.

Light scattering devices designed to measure the concentration of airborne particulate matter continuously, may be used as supplement to gravimetric measurements. Aerosol monitors are available with a wide concentration measurement range. Devices based on the light scattering

principle determine the volume of the particles in a suspension. The weight is found by calibration against test dust with known density and particle size distribution.

The EUROVENT 4/9 *fractional efficiency method* may also be modified and adapted for field studies if the natural occurrence of particles in the air has a satisfactory concentration. The distance between upstream and downstream measuring sections will decide if one can use a single laser system based on successively upstream and downstream measurements, or if one has to choose a co-calibrated dual laser system. Experience has shown that transfer lines above 8 metres may cause significant dust precipitation in the lines. Also large time dependent variations in the upstream dust concentration will not favour the successive method, even if the counts are within the counter measurement range. For large installations like EP in tunnels, the successive method using one-way valves and long transfer lines to switch between the upstream and downstream section is not recommended. A dual system using one counter upstream and one counter downstream may eliminate the transfer line approach. However, the usefulness of such a system depends on the co-calibration of the two devices. In Norway, distributors of laser particle counter who have been contacted cannot guarantee satisfactory co-calibration.

Based upon the above discussion, it has been decided that the weight efficiency test in the Chinbu tunnel should be carried out by using two real-time light scattering aerosol

The fractional efficiency test should be carried out by using the successive fractional efficiency method. To avoid long transfer lines, the efficiency test will be executed by using one laser particle counter manually moved between the upstream and downstream measuring sections.

### **3.3 Instrumentation and test procedures**

As a suitable device for real-time aerosol measurements and gravimetric measurements, the light scattering device pDR-1200 from Monitoring Instruments of the Environment Inc. has been chosen. The pDR-1200 has a concentration measurement range from 0.001 to 400 mg/m<sup>3</sup>. The repeatability is  $\pm 1\%$  of reading or  $\pm 0.001$  mg/m<sup>3</sup>, and the stated accuracy is  $\pm 5\%$  for a 10-second averaging measurement. The instrument has a built-in filter holder for gravimetric measurements on membrane filter.

The laser particle counter MetOne M200L has been chosen as a device for particle counting. The MetOne counter has a particle size range from 0.3 – 10  $\mu\text{m}$ . Counts are distributed into six ranges (0.3-0.5  $\mu\text{m}$ , 0.5-1.0  $\mu\text{m}$ , 1.0-2.0  $\mu\text{m}$ , 2.0-5.0  $\mu\text{m}$ , 5.0-10  $\mu\text{m}$  and  $>10$   $\mu\text{m}$ ). The device has a coincidence error less than 5% at 100000 particles/litre.

While standards ASHRAE 52 and EUROVENT 4/9 recommend isokinetic sampling from one spot upstream and downstream of the cleaning device, measurements on large devices with a face area of several square metres should have measuring sections with several isokinetic spots. A measuring section covered by several spots will better reflect the average dust concentration upstream and downstream of the cleaning device. To avoid time-consuming tuning of the airflow from each spot, transfer lines have been arranged so that the transfer distance from the measuring device to each spot is equal. This will ensure that the sample flow from each spot is identical.

Figure 3.1 shows the transfer line arrangement for weight measurements used in the Chinbu tunnel. The sampling system is based on a symmetric transfer line network with 8 spots. Adjustment valves are used to obtain isokinetic samples and constant flow through the light scattering device and the dust spot target filter. A corresponding system covers the particle counter. For detailed layout and location of measuring spots see Appendix A

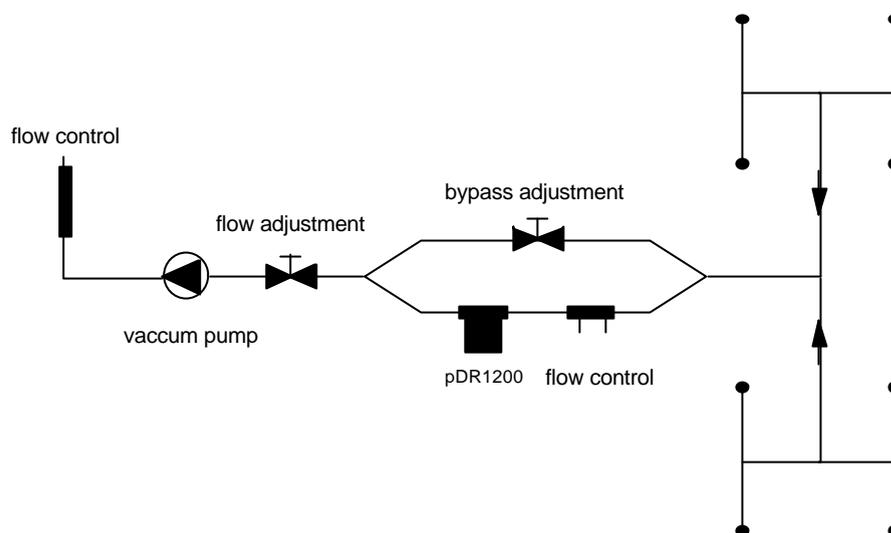


Figure 3.1 Transfer line arrangement for upstream/downstream weight measurement

Fractional efficiency is determined by moving the particle counter successively between the upstream and downstream transfer line arrangement. The dust sampling period at one location has been set to 10 minutes. The counting interval for the MetOne is set to 1 minute. The time to move and connect particle counter between each repetition is approximately 5 minutes. Total measuring period is 3 hours and 15 minutes. Upstream/downstream repetitions have been carried out in accordance with EUROVENT 4/9

Weight arrestance efficiency is determined by comparing results from the two pDR 1200 aerosol monitors loaded with membrane filters for both electronically and gravimetrically evaluation. One monitor samples the dust concentration upstream the cleaning system, the other monitor samples the dust concentration downstream the cleaning system. The total measuring period is 3 hours and 15 minutes. Sampling interval for the electronic devices is set to 30 seconds, and stored values are 30 second average values. The particle test and the weight arrestance test are run in parallel.

## 4 TEST RESULTS

### 4.1 Test conditions

The efficiency tests have been repeated three times as prescribed in the contract between CTA International and Doosan Construction and Engineering. First test was carried out on Tuesday 1999-10-19, the second-test was carried out on Wednesday 1999-10-20 and third test was carried out on Thursday 1999-10-21. Two tests were carried out with airflow of 285 m<sup>3</sup>/s. In order to get some information about the flow sensitivity of the filter-system, the third test was carried out with a flow reduction of 5 %.

The velocity-profile 1.0 m downstream the EP-section was measured with nominal airflow with a Swema hot-wire anemometer. The results are presented in Figure 4.1. The average value is 4.5 m/s.

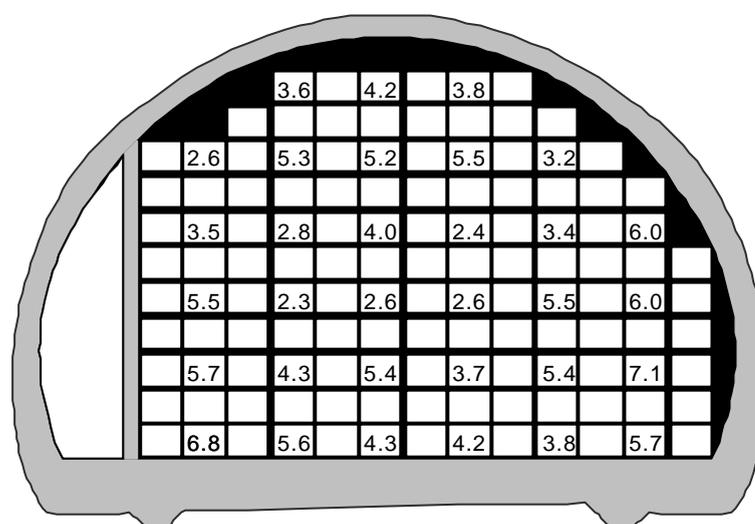


Fig. 4.1 Velocity-profile EP-section (all values in m/s).

Before the test-period started, the road surface in the bypass tunnel was cleaned with pressurised water. This was done to avoid unwanted dust raising. However, the corridor passing the air cleaning units was not cleaned.

During the second and third tests the number of cars passing through the tunnel was automatically counted from the traffic control centre (the possibility of doing this was not known during the first test). The counting-results are presented in Table 4.1

Table 4.1 Traffic count during Tests 2 and 3

Date	Trailer	Truck/bus	2.5t	1t	Passenger	Total count
1999-10-20	95	24	643	474	1431	2667
1999-10-21	109	34	256	373	1274	2046

During these tests the traffic situation was also video-recorded. The recordings show that the traffic passing through the tunnel mainly is grouped in clusters containing 5 to 20 vehicles. Measurements of the upstream dust concentration reflect this traffic situation very well (see Fig 4.3).

Climate parameters such as air temperature and humidity were recorded during the tests. Also the outside weather conditions were observed. During all three test periods the outside weather was sunshine. The air temperature varied from 12.4 °C to 15.1 °C, and the humidity measurements show variations from 44 % to 53 % RH.

The voltage in the EP cells was also recorded. Primary voltage was measured to be 220V, the ionizer voltage was measured to be 12.6 kV and collector voltage was measured to be 6.2 kV.

Due to technical problems, the fans in the main tunnel were not running during the tests. The airflow through the main tunnel was caused by the traffic, and it is observed that the flow has varied significantly.

#### 4.2 Fractional efficiency based on particle counting

Figure 4.2 shows the average particle concentration measured upstream and downstream of the cleaning system. The upstream values are calculated from 70 one-minute readings from the particle counter. The downstream values are based on 60 one-minute readings. Comparing single upstream readings with average values shows large fluctuations, especially for coarse particles. While fluctuations typically are 1 to 3 for the finest particles, variations of 1 to 50 have been registered for fractions above 10  $\mu\text{m}$ .

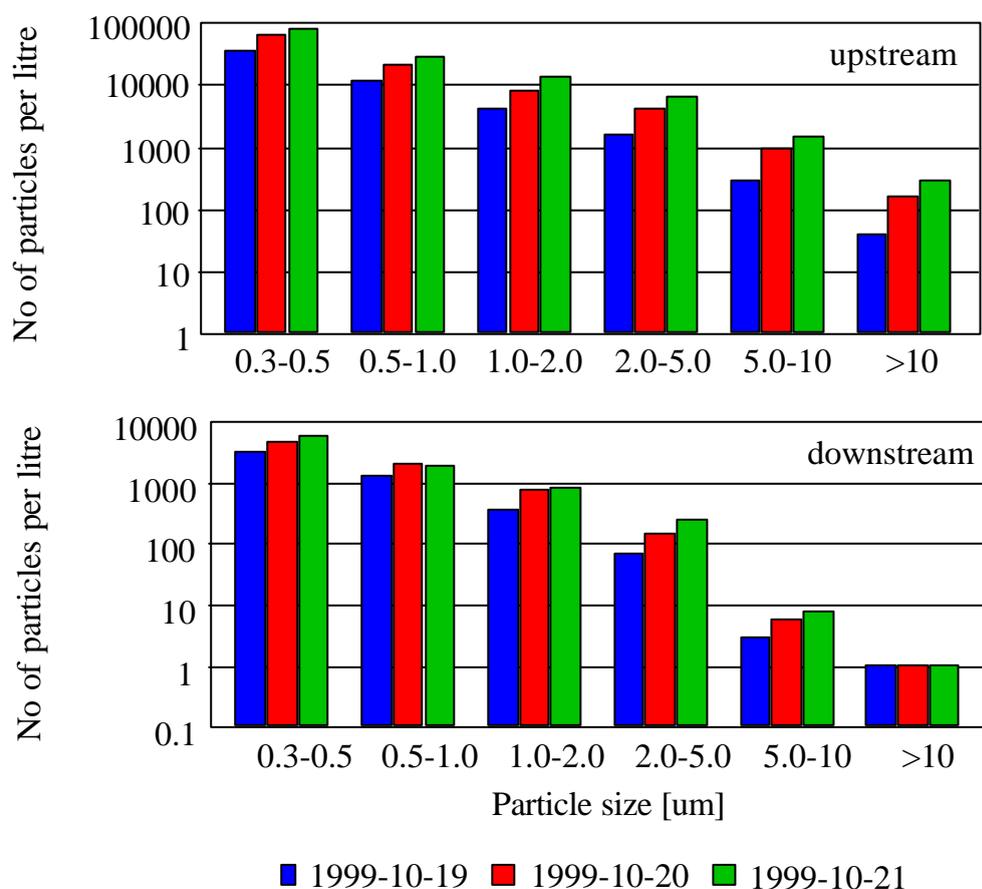


Figure 4.2. Particle counts upstream/downstream of the cleaning system.

Particle efficiency for each fraction measured was calculated by using Equation (3) in Section 3.1. The results of these calculations are shown in Figure 4.3.

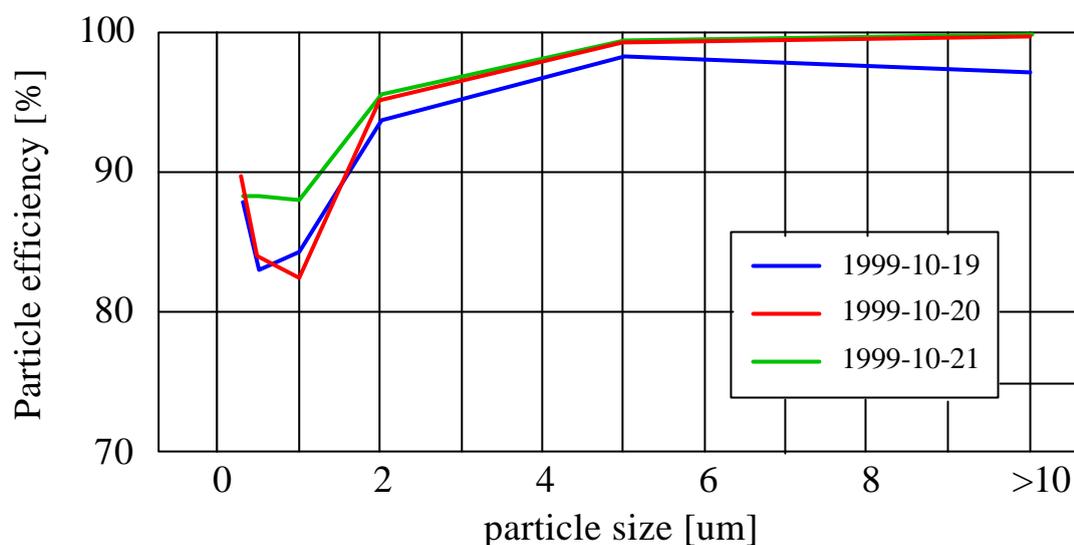


Figure 4.3. Fractional efficiency (0.3  $\mu\text{m}$  and above)

Test 1 (1999-10-19) and Test 2 (1999-10-20) were carried out with identical airflow. Still, Test 1 shows somewhat lower efficiency. It is most likely that the power supply dropout during first period of the test has caused this result. Power supply dropout was corrected for by adjusting the thermal-fuses from 2 to 3 amps in the middle of the test period (see also Figure 4.5).

Test 3 (1999-10-21) was carried out with a 5 % flow reduction. The flow reduction seems to have most impact on particles less than 2  $\mu\text{m}$ .

In the contract between CTA International and Doosan, it is said that the efficiency for particle fraction 0.3 – 10  $\mu\text{m}$  should be 92 % or more. By integrating the curves shown in Figure 4.3, an average efficiency for this particle range can be calculated. Table 4.2 shows the results based on this calculation method.

Table 4.2 average particle efficiency (0.3 – 10  $\mu\text{m}$ )

	efficiency
1 <sup>st</sup> test (1999-10-19)	93.8 %
2 <sup>nd</sup> test (1999-10-20)	94.8 %
3 <sup>rd</sup> test (1999-10-21)	96.9 %

### 4.3 Weight efficiency based on light scattering measurements

Figure 4.4 shows the mass concentration measured upstream and downstream of the cleaning system. Upstream/downstream concentration has been recorded continuously for 3 hours and 15 minutes. Curves presented are based on 30 second average values. Concentration curves presume a dust bulk density of  $2.6 \text{ g/cm}^3$ . However, additional tests have shown that the density varies widely with respect to time and location. Curves presented may therefore represent dust volume more than dust weight.

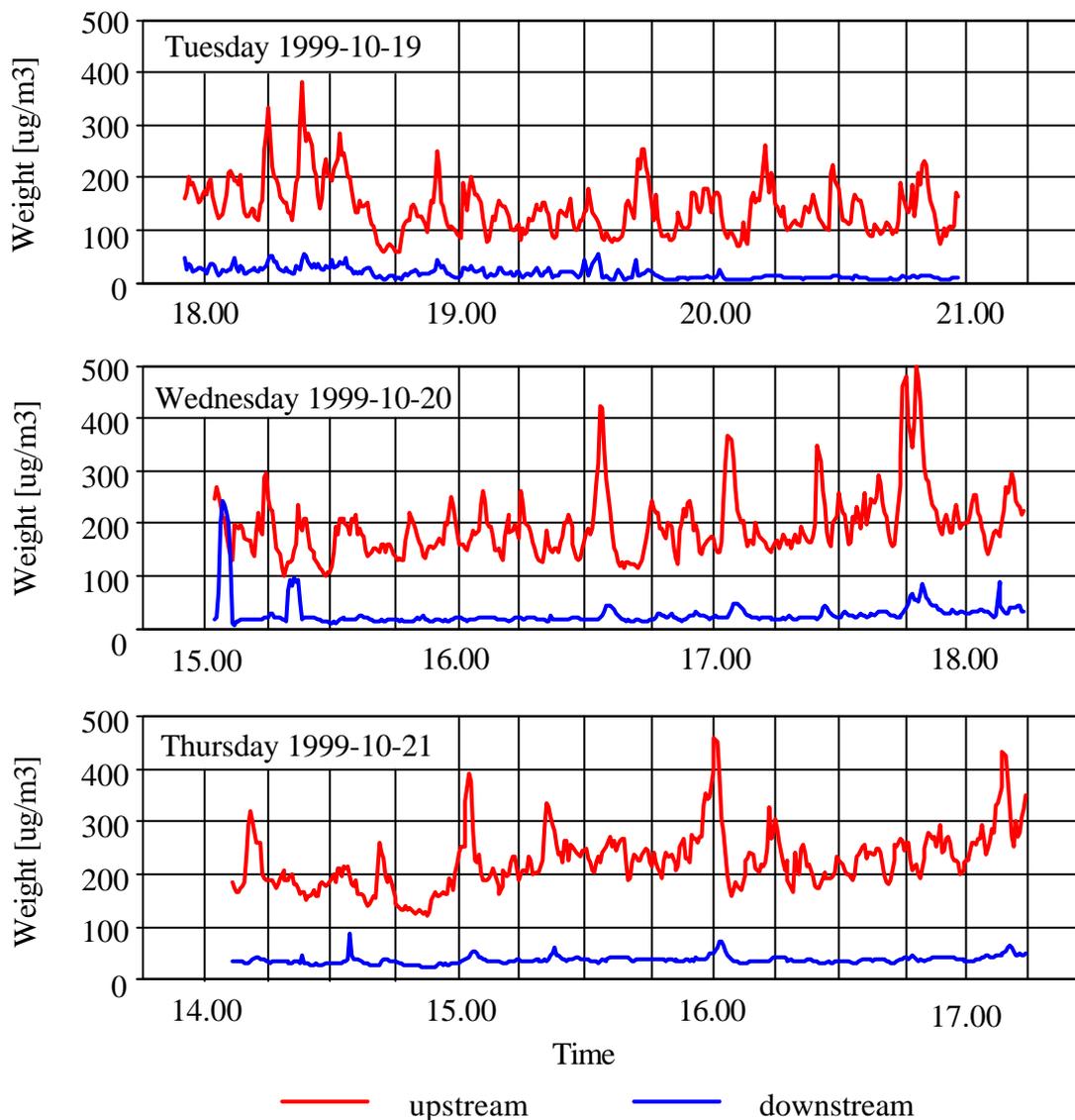


Figure 4.4 Light scattering measurements upstream/downstream of the cleaning system

Also the light scattering measurements confirm that the dust concentration is varying widely due to time. The time average concentrations upstream for Test 1 to 3 are respectively 150, 197 and  $217 \mu\text{g}/\text{m}^3$ , maximum 30 second average recorded on Wednesday 1999-10-20 at 17.48 is  $516 \mu\text{g}/\text{m}^3$ .

The measurements of the downstream concentration on Wednesday 1999-10-20 show two dust-peaks between 15.00 and 15.30. These peaks are caused by two system shutdowns at the beginning of the test period (PLC malfunctions).

Weight (volume) efficiency has been calculated in accordance with Equation (2) in section 3.1. The time-dependent efficiencies are presented graphically in Figure 4.5.

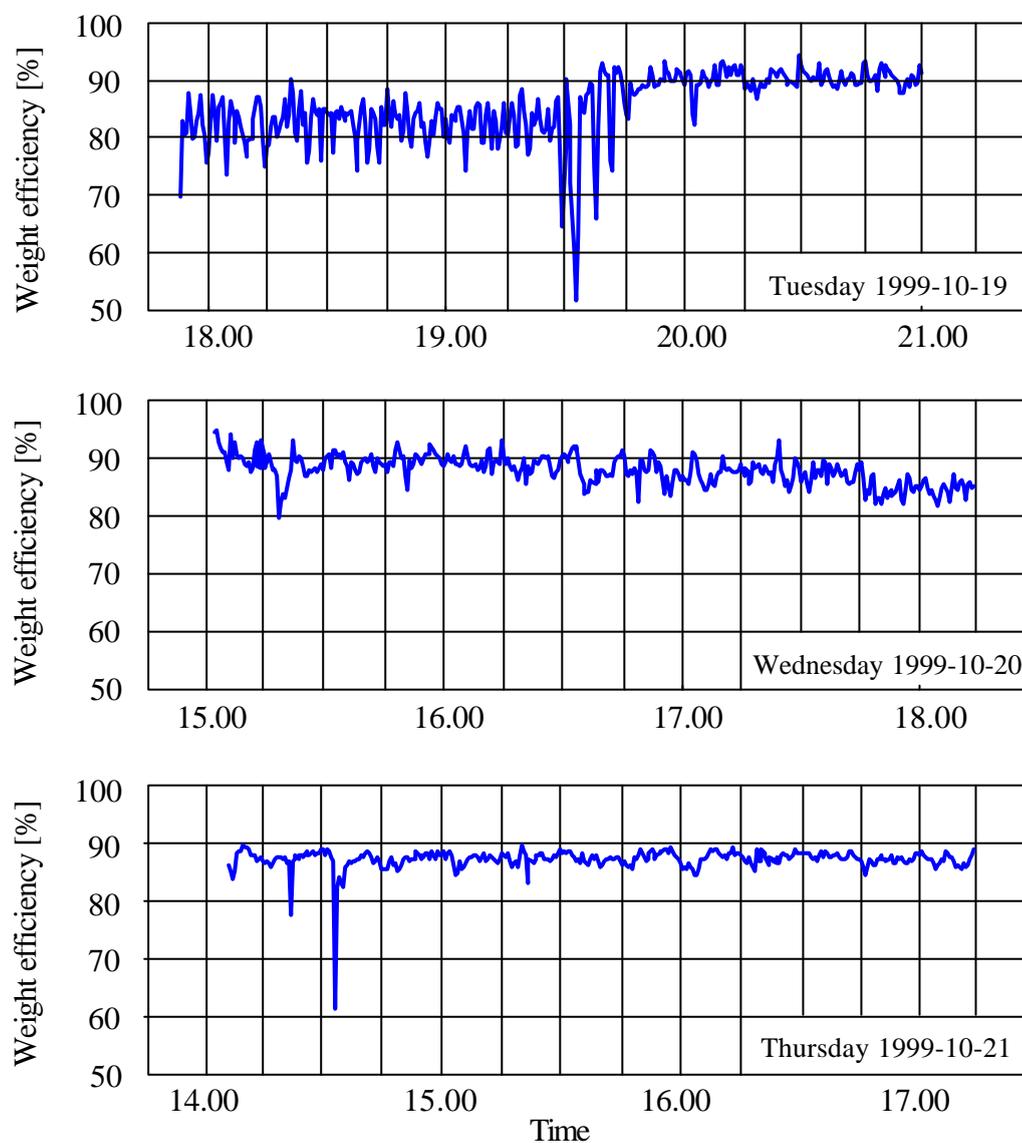


Figure 4.5 Time-dependent weight (volume) efficiencies

Efficiency Test 1 (1999-10.19) clearly shows the effect of the power-supply dropout during the first period of the test (17.40-19.30). According to our own observations 4 power-systems were arbitrary shut down during this period. At 19.30 all systems were shut down and thermal-fuses were adjusted.

Efficiency Test 3 (1999-10-21) shows two dips between 14.00 and 15.00. Opening the door between the bypass-corridor and the dirty water tank area have caused these dips. The dips

clearly show the consequence of dirt flowing from the bypass corridor to the clean side of the air cleaning system.

Table 4.3 presents the average weight efficiencies based on light scattering measurement. Test 1 is divided into two results, before and after thermal-fuse adjustment. Test 3 is presented with dips removed.

Table 4.3 Average weight (volume) efficiency based on light scattering

	Weight efficiency	Weight efficiency
Test 1 (1999-10-19)	82.8 %	90.4 %
Test 2 (1999-10-20)	85.6 %	
Test 3 (1999-10-21)	87.6 %	

## 5 DISCUSSION

At the moment there are no standards covering full-scale efficiency testing of air cleaning systems installed in road tunnels. In this project, three different types of measuring principles have been used to determine the particle and weight efficiency of the cleaning system installed in the Chinbu tunnel – South Korea.

All measuring methods chosen have their limitations. The particle efficiency test based on successive measurements upstream and downstream of the cleaning system, demand steady state dust concentration during the test period. In addition, the particle counter should be moved between upstream and downstream measuring sections without short circuiting the cleaning system. None of these conditions have been met during the tests.

Light scattering measurements assume that the bulk density of the dust is known. Analysis has shown that the bulk density varies widely due to time and location. Most likely continuously traffic with diesel engines gives large portion of organic dust, while intermittent traffic with vehicles grouped in clusters raise a lot of mineral dust from the roadway. The light scattering devices used in this project have a particle size range of maximum response 0.1 – 10  $\mu\text{g}$ . How these instruments behave when particles are 200  $\mu\text{g}$  is not known.

APPENDIX A - LOCATION OF MEASURING SPOTS AND SECTIONS

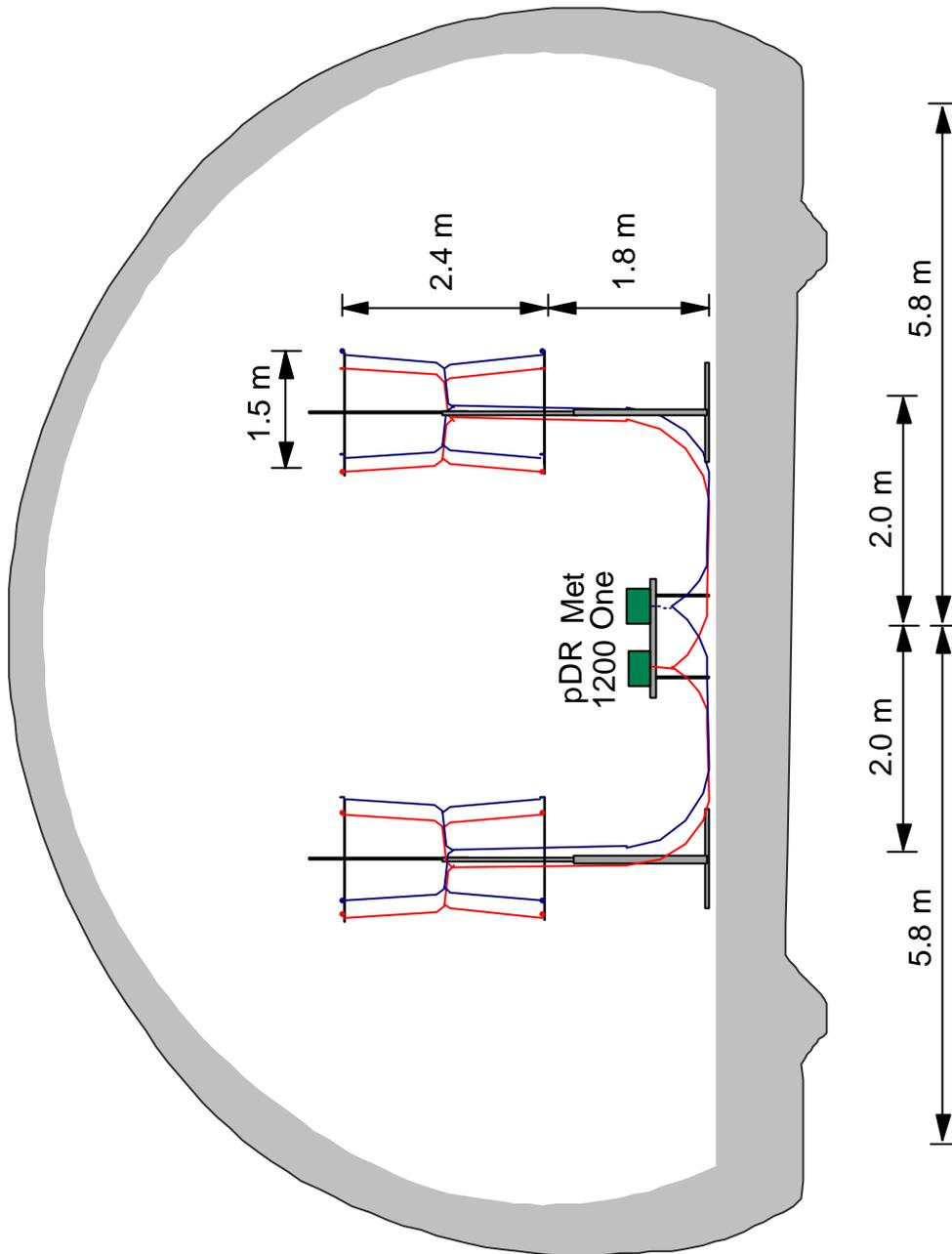


Figure A.1 Location of measuring spots upstream/downstream the measuring sections

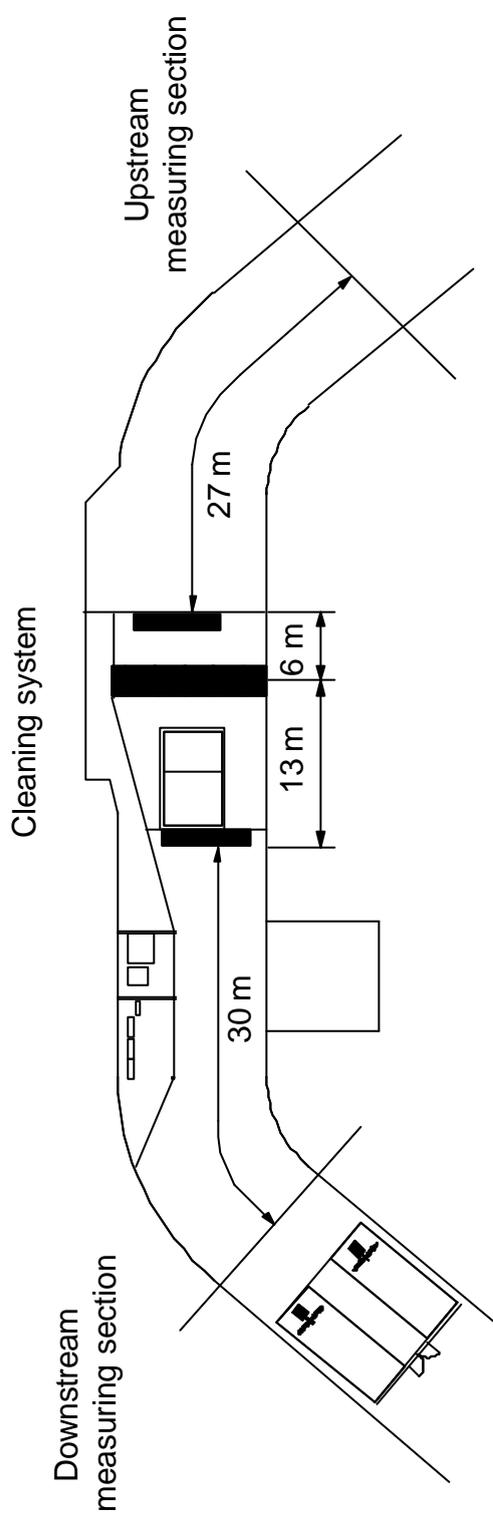


Figure A.2 Location of upstream and downstream measuring sections