An air cleaner for road tunnels

LEI Yuyong1, LI Xiaohong2, YANG Lin3
1 Sichuan University of Science and Technology, Chengdu 610039, P.R. China
2 Chongqing University, Chongqing 400044, P.R. China
3 Zuzhou Institute of Technology, Zuzhou 412008, P.R. China

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Abstract: an air cleaner employing pulse induced plasma chemical process to remove dust and carbon monoxide (CO) in road tunnels is presented, which is composed of mainly a precipitator, a reactor, a flow control system, a power supply and a measurement system. Its performances are studied in simulated air conditions. It is found that the rate of dust removal is dependent on the voltage of the pulse power, the distance between the two dust collecting plates of the electrostatic precipitator, the effective length of the precipitator and the air flow rate in the precipitator, and that of CO removal is affected by the voltage and frequency of the super pulse power, the air flow rate in the reactor and the relative humidity of air. Applying such an cleaner of a proper design to the treatment of polluted air at a flow rate of 7 m/s can achieve the rate of dust removal up to 93 % and that of CO removal up to 72.6 %, which efficiently controls the concentrations of CO and dust under allowable limits. It is implied that the proposed air cleaner is a potential solution to air control in road tunnels, and is prominent for its performances and saving the huge cost of longitudinal ventilation tunnel or vertical vent and ventilation facilities.

Keywords: air pollution; air pollution control; dust removal; road tunnel; CO removal

1. Introduction

With the development of transportation, more and more road tunnels, especially the long tunnels, such as Erlangshan Tunnel (4176 m, China), Arlberg Tunnel (13972 m, Austria), Kan-etsu Tunnel (11055 m, South tube, Japan) and Laerdal Tunnel (24510m, Norway) have been built on the highway lines [1]. In a road tunnel, the exhaust gases given off by automobile engines, such as smoke, carbon monoxide (CO), oxynitride (NOx), hydrocarbon, etc., and dust produced by the passing automobiles are increasingly concentrated. Because it is difficult for these pollutants to diffuse, the air in the tunnel is heavily polluted.

CO in the exhaust gases is a poisonous pollutant. It may poison drivers and passengers by suffocating them when its concentration goes beyond the limit. Smoke and dust produced by the passing automobiles do harm to the health of passengers and drivers, and decrease drivers’ visibility when gather to a high concentration hence may cause car accidents. Therefore, CO and smoke-cloud are universally taken as principal pollutants in road tunnels, and their limits, generally 150 μL/L and 9×10−3 m−1 respectively, are recommended [2].

The concentration of smoke-cloud \( K_i \) is defined as follows [3].

\[
K_i = \frac{1}{L} \ln \frac{1}{\tau} \tag{1}
\]

where \( \tau \) is the light passing rate given by \( \tau = E/E_0 \), in which \( E_0 \) and \( E \) are the light flux at light source and that traveling a distance \( L \) respectively.

Conventionally the concentration of CO and visibility distance in the road tunnel are controlled by ventilation [3]. It is not an economic way due to huge investment in building a ventilation tunnel and facilities as well as high operation cost, wherefore this research means to find other methods and technologies to treat the polluted air in road tunnels.

There are various methods and devices for the pollution control, such as catalytic oxidation, wet or dry scrubber, electrostatic precipitator, etc. They are generally ineffective as applied to road tunnels directly since the air flow rate is as high as (7 to 10) m/s due to the required ventilation volume. A prior work by the authors revealed that satisfying results in CO removal can be obtained by using pulse induced plasma chemical process (PPCP) [4-6]. Meanwhile, it is known that an electrostatic precipitator has better performance and is more efficient by supplying pulse voltage. Those are...
the fundamentals in this work to develop the simple prototype of an air cleaner for road tunnels (ACRT). Performances of the ACRT is also measured and analyzed.

It is known that the smoke produced by automobile engine is actually composed of very tiny porous carbonic particulates with an average diameter of 0.1 μm to 10.0 μm [1]. Because it is difficult to measure in laboratory the concentration of smoke-cloud as defined previously, the bulk concentration of cement dust is to be measured and analyzed instead.

2. Prototype of the air cleaner

Fig. 1 illustrates the structure of the ACRT prototype mainly composed of five parts, i.e. a precipitator, a reactor, a flow control system, a power supply and a measurement system. In this work, the precipitator was made of wire-to-plate, whose internal section area was 400 mm × 260 mm. The distance of two dust collecting plates was adjustable in the range from 255 mm to 395 mm.

![Fig.1 Schematic diagram of the ACRT](image)

The reactor to oxidize CO consists of many a coaxial wire-to-cylinder electrode system. The copper wire of a 2.5 mm diameter was suspended along the axis of a stainless steel cylinder. The internal diameter of the cylinder varied in the range from 50 mm to 100 mm and the thickness of the cylinder was 2 mm. The effective length of the reactor was 3000 mm.

The pulse power supplied to electrostatic precipitator was generated by a capacitor bank and a rotating spark gap. The capacitor bank was charged by a DC high voltage source and discharged through the rotating spark gap. The super pulse power supplied to the reactor for oxidizing CO was generated by a fast pulse capacitor bank and a rotating spark gap, so a super narrow pulse voltage was obtained, as shown in Fig. 2. The parameters of pulse power and super pulse power were as follows.

\[
V_1 = (0 \text{ to } 120) \text{ kV} \quad f_1 = 50 \text{ Hz} \quad t_{11} \leq 100 \mu s \quad t_{12} \leq 250 \mu s \quad V_2 = (0 \text{ to } 60) \text{ kV} \quad f_2 = (0 \text{ to } 100) \text{ Hz} \quad t_{21} \leq 50 \text{ ns} \quad t_{22} \leq 300 \text{ ns}
\]

The positive pole of the high voltage pulse was applied to the inner copper wire electrodes of the precipitator and the reactor.

KG9201 CO analyzer was used to measure the concentration of CO. The airflow rates inside the precipitator and reactor were adjusted to control the flow rate inside the ACRT, and the concentrations of smoke, dust, and CO. In such a way, the air condition in a road tunnel was simulated in the laboratory. The ambient temperature and relative humidity of the air inside ACRT were recorded. The experimental parameters were set as follows:

\[
C_\infty^0 = 150 \text{ μL/L}, \quad C_d^0 = 23 \text{ mg/m}^3, \quad G_d = (0.5 \text{ to } 15) \mu \text{m}, \quad v_1 = v_2 = (2 \text{ to } 7.5) \text{ m/s}, \quad H_r = 44 \% \text{ to } 95 \%
\]

3. Experimental results

3.1 Results of dust removal

The rate of dust removal \( R_d \) is given by the ratio of
the dust concentration $C^0_d$ at the outlet of ACRT to that $C^0_d$ at the inlet. As can be seen in Fig.3, the rate of removal of dust increases generally when the supplied voltage $V_1$ goes up and the distance $X$ between two dust collecting plates (i.e. the distance between electrode and dust collecting plates) reduces. Obviously stronger corona is formed when the supplied voltage is higher and the distance between electrode and dust collecting plates is shorter. Therefore higher dust removal rate can be obtained. It must be noted that the supplied voltage cannot be further enhanced when it reaches certain value (e.g. 60 kV) because spark discharge will start.

The rate of dust removal rises when the air flow rate inside precipitator slows down, as shown in Fig.4. Apparently the charging time of particles and residence time of the charged particles are longer when the air flow rate decreases. Hence the dust attached to the collecting plates increases. Moreover, the dust concentration $d$ is shown in Fig.5 which indicates a steady increase in $R_d$ with a longer precipitator. This is because the longer the precipitator, the longer the residence time of the dust inside the precipitator, and therefore the more the collected dust. However the dust removal rate is slightly declined when the length of the precipitator is longer than 10.8 m. The reason for this may be that the dust deposited on collecting plates flies back into the air again. So the dust removal rate falls.

From Figs.3 to 5, the highest $R_d$ of 93 % is achieved when $X=255$ mm, $L_p=10.80$ m, and $V_1=60$ kV.

3.2 Results of CO removal

Fig. 6 shows the rate of CO removal $R_{CO}$ changing with the pulse voltage amplitude, taking the upper limit of CO concentration $C_{CO}^0 =150 \mu L/L$ as the initial value. It can be seen that $R_{CO}$ increases with increasing voltage at a fixed frequency. This is because more power delivered into the discharge produces more radicals. However, $R_{CO}$ is not influenced significantly by a voltage above 56 kV. This is resulted from the equilibrium of oxidization process. For this reason, the tendency of the curve becomes gentle at a high voltage.

The way the effective length of the precipitator $L_p$ affects $R_d$ is shown in Fig.5 which indicates a steady increase in $R_d$ with a longer precipitator. This is because the longer the precipitator, the longer the residence time of the dust inside the precipitator, and therefore the more the collected dust. However the dust removal rate is slightly declined when the length of the precipitator is longer than 10.8 m. The reason for this may be that the dust deposited on collecting plates flies back into the air again. So the dust removal rate falls.

The influence of the air flow rate $v_1$ in the reactor on
$R_{CO}$ is shown in Fig. 7. $R_{CO}$ decreases significantly in the case of larger $v_2$. Obviously, the amount of CO to be treated is larger at a higher $v_2$, and on the other hand, the residence time of the CO in the reactor becomes shorter. Therefore, the process of CO oxidation is not sufficient and results in a lower $R_{CO}$.

![Graph showing dependence of $R_{CO}$ on $v_2$.](image)

**Fig. 7. Dependence of $R_{CO}$ on $v_2$.**

It is suggested in Fig. 8 that higher $R_{CO}$ can be achieved by humidifying properly, attributed to the increase of radicals OH* in a discharge at a higher relative humidity $H_r$ [5]. However, the inception of discharge will be decreased by a relative humidity too high, which results in the decrease in the numbers of O and O3 and hence the slowdown of CO oxidation. The highest $R_{CO}$ is achieved at relative humidity $H_r = 88 \%$.

![Graph showing dependence of $R_{CO}$ on $H_r$.](image)

**Fig. 8. Dependence of $R_{CO}$ on $H_r$.**

### 4. Conclusions

The performances of the proposed air cleaner for road tunnels (ACRT) employing pulse induced plasma chemical process are significantly influenced by the voltage of the pulse power, the distance between the two dust collecting plates of the electrostatic precipitator, the length of the electrostatic precipitator, the voltage and frequency of the super pulse power, the air flow rate and the relative humidity. Application of a properly constructed ACRT to the simulated condition of a road tunnel at an air flow rate up to 7 m/s can achieve a rate of dust removal as high as 93 % and that of CO removal up to 72.6 %.

Such an air cleaner makes it possible to ventilate longitudinally in the whole tunnel just using jet fans, no matter how big and how long the tunnel is. It also saves the huge cost for building a longitudinal ventilation tunnel (or vertical vents) and installing ventilation facilities. It is a promising solution to the treatment of polluted air in road tunnels.

### Notations

- $C_{COi}^0$: volume concentration of CO at inlet.
- $C_{COe}^0$: volume concentration of CO at outlet.
- $C_{d}^0$: inlet concentration of dust.
- $C_{d}^e$: outlet concentration of dust.
- $V_1$: peak amplitude of voltage of the pulse power
- $V_2$: peak amplitude of voltage of the super pulse power
- $f_1$: frequency of the pulse power.
- $f_2$: frequency of the super pulse power.
- $t_1$: rising time of the pulse voltage $V_1$.
- $t_2$: duration of the super pulse voltage $V_2$.
- $D$: diameter of the reactor for oxidizing CO.
- $L_P$: length of the electrostatic precipitator.
- $L_R$: length of the reactor for oxidizing CO.
- $X$: distance between the two dust collecting plates of the electrostatic precipitator.
- $A$: sectional area of electrostatic precipitator
- $v_1$: air flow rate in the precipitator.
- $v_2$: air flow rate in the reactor.
- $G_d$: granularity of dust.
- $H_r$: relative humidity of polluted air.
- $R_d$: rate of dust removal.
- $R_{CO}$: rate of CO removal.

### References