Experimental Study on the Dispersion of Chemical Species in the Automobile Exhaust Gas Using a Scale Model

J. Onishi[1], A. Nakata[1], A. Kaga[2], Y. Inoue[2], A. Kondo[2], S.Shi[2] and Y.H. Chung[3]

1: Dept. Mechanical Engineering, Osaka Electro-Communication Univ., Osaka JAPAN

2: Dept. of Environmental Engineering, Osaka Univ., Osaka JAPAN

3: Dept. of Environmental Engineering, Pukyong National University, Busan KOREA

Corresponding author ***J.Onishi***

Abstract

The aim of our study is to establish a prediction model of chemical species dispersion applicable to making data maps in various areas. In the present study, a fundamental experiment was performed using a scale model of a road with a simple roadside configuration in order to investigate the relations between the roadside buildings and the dispersion of the chemical species under a wind blowing condition. As a scale model, a water filled duct circuit was used. The cross sectional area of the test section is 100×80mm. Both flow and concentration distributions were measured at the central cross section assuming the flow field to be two-dimensional. The flow fields were visualized with nylon tracer particles and a twin Nd-Yag laser light source the maximum output of which is 120mJ. The visualized image data was stored in a computer memory through a CCD cross correlation camera ($1280\times1024\text{pixel}^2$) and was analyzed with an image processing technique, PIV (Particle Image Velocimetry). As a contamination tracer, small bubbles were used. In order to supply the tracer bubbles, a hydrogen bubble method was applied. Regarding the bubbles as a toxic substance, their dispersion was visualized with a laser light sheet and recorded by a CCD video camera. The recorded data was analyzed through an image processing technique. Measured data of flow and concentration fields seems to be acceptable and will be rearranged to examine some numerical prediction models.

Keyword: *automobile exhaust gas, dispersion, scale model, PIV, hydrogen bubble method*

1. Introduction

Although various toxic substances are included in the automobile exhaust gas, benzene is one of the highly carcinogenic chemical species. Recent investigations on benzene contamination indicate that approximately 75% of the total amount is emitted by automobiles in our country [1]. It is also observed through field measurements that the concentration often exceeds the environmental standard at the roadsides [2],[3]. This suggests that some immediate measures should be necessary to control the benzene concentration along the roadside.

The aim of our study is to develop a simplified prediction model of chemical species dispersion applicable to making data maps in various urban areas. In order to realize the aim of our study, step by step approach should be necessary. Firstly, a numerical calculation method (a CFD code) should be prepared and be tested using some reliable experimental data. Secondly, a more simplified prediction model (a macro model) in which flow or concentration fields is not calculated should be developed using the data derived from the CFD code investigations. Finally, the macro model is applied to making some data maps for various urban areas after validating it with the data obtained through field observations.

In the present study, a fundamental experiment was performed using a scale model of a road with a simple roadside configuration in order to prepare reliable data to validate some numerical methods which may be applicable to investigating the relations between the various roadside configurations and the dispersion of the chemical species under a wind blowing condition. As the scale model, a water filled duct circuit was used. Both flow and concentration distributions were measured at the central cross section assuming the flow field be two-dimensional.

The flow fields were visualized with nylon tracer particles and a twin Nd-Yag laser light source the maximum output of which is 120mJ. The visualized image data was stored in a computer memory through a CCD cross correlation camera (1280×1024pixel^2) and was analyzed with an image processing technique, PIV (Particle Image Velocimetry). As a contamination tracer, small bubbles were used. In order to supply the tracer bubbles, a hydrogen bubble method was applied. Regarding the bubbles as a toxic substance, their dispersion was visualized with a laser light sheet and recorded by a CCD video camera. The recorded data was analyzed through an image processing technique. Measured data of flow and concentration fields seems to be acceptable and will be rearranged to examine some numerical prediction models.

2. Experiment

2.1 Outline of experimental setup

As a scale model of the condition that natural wind is blowing across a road, a water filled duct system is applied. Schematic of experimental setup is shown in Fig.1. The test space has a rectangular cross section the sizes of which is 100×80mm. A flow rectifier inserted upstream the test section realizes almost uniform velocity distribution across the duct cross section. Assuming the flow field is two dimensional, flow and concentration fields were measured only at the central vertical cross section.

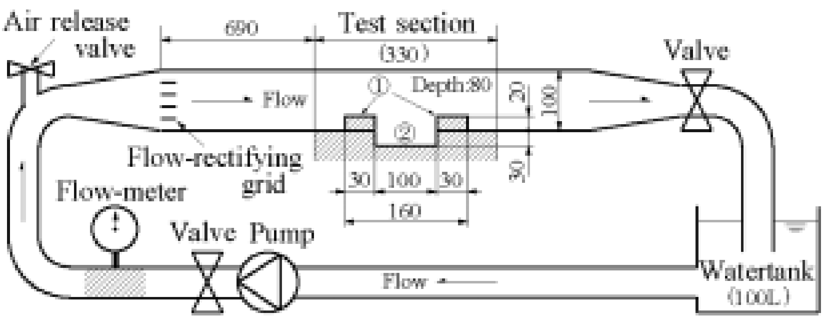

Fig.1 Schematic of experimental setup.

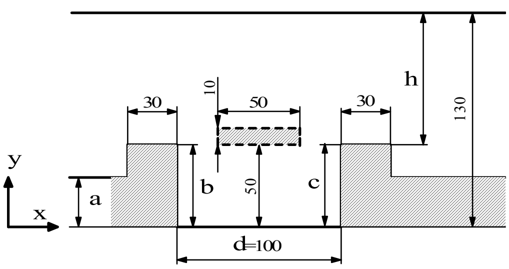

Fig.2 Detail of test section.

Detail of the measured section is shown in Fig.2. In Fig.2, a is averaged height of buildings next to the roadside buildings, b and c are height of roadside buildings and d is the width of the road. An obstacle shown with dotted line is a highway running above the road. Taking the configuration of the test section as an experimental parameter, experiments were carried out on four conditions. They are shown in Table 1. The water flow rate was kept constant at 64ℓ/min throughout the measurements. Then, the approaching velocity averaged in the duct cross section is U=13cm/s and the Reynolds number based upon U and the hydraulic diameter of the duct d_h becomes Re=1.2×10^4. Consequently, the water flow in the duct can be regarded as well-developed turbulent one. This may suggest that the similarity law between the flow properties measured in the scale model and the actual wind condition around the real road configuration is approximately maintained.

Table 1 Experimental conditions.

case1	a=50, b=50, without highway
case2	a=50, b=70, without highway
case3	a=70, b=50, without highway
case4	a=50, b=50, with highway

2.2 Velocity measurement

Velocity vectors in the test section (Fig.2) were measured using a PIV (Particle Image Velocimetry) system. The flow fields were visualized with nylon tracer particles and a twin Nd-Yag laser light source the maximum output of which is 120mJ. The diameter of the tracer particles is 40μm and its specific weight is 1.02. The measuring method is as follows: Two image sets lit up by the double pulse Nd-Yag laser are continuously stored in a computer memory through a CCD camera ($1280\times1024pixel^2$) synchronized with the laser pulse emitting. In the results shown below, the interval of the laser pulse emission (straddling time) is set 5~8ms and sampling frequency of the image sets is 1.85 Hz. The visualized image data sets are analyzed with a cross correlation method to obtain instantaneous vector images. In the analyzing process, the interrogation area was set $16\times16pix^2$. The each instantaneous vector image is superimposed to get a time averaged flow field.

2.3 Concentration measurement

A contamination source is placed at the road surface ((2) in Fig.1). As a contamination tracer, small bubbles were used. In order to supply the tracer bubbles, a hydrogen bubble method was applied. As is shown in Fig.3, two electrodes, one is fine stainless wires the diameter of which is 0.3mm, and the other is a punched stainless sheet, are placed on the road surface. When both electrodes are charged by electric power, small hydrogen bubbles are emitted from the stainless wires. Regarding the bubbles as a tracer of the toxic substance, their dispersion was visualized with a laser light sheet (Argon laser, 1W) and recorded by a CCD video camera.

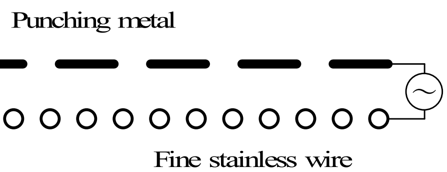

Fig.3 Cross section of hydrogen bubble generator.

The concentration value is expressed by recorded gray level on the video images, however, it is influenced by the laser sheet strength and the concentration level for each experimental case since they are not uniform in the whole area of the lit up sheet for each experimental case. Moreover, the concentration level have different values among the experimental cases. In order to correct the gray level non-uniformity, two additional images were recorded in each case before taking the tracer images, one is a background images in which no tracer exist and only the test section is lit up by the laser sheet, the other is uniform concentration images under the condition that water is stagnant and something diffusible substance like ink or die is mixed and stirred to be uniformly distributed. As a diffusible substance milk was used in this study. The data analyzing process to derive an averaged concentration image for each experimental case is as follows:

(1) 100 digital gray level images are made through A/D conversion of the tracer video images sampled at the time interval 2sec, then, they are superimposed to make an averaged gray level tracer image (Tr_{avg}).

(2) 30 digital gray level images are made through A/D conversion of the background video images sampled at the time interval 1sec, then, they are superimposed to make an averaged gray level background image (Bk).

(3) 30 digital gray level images are made through A/D conversion of the uniform concentration video image at the time interval 1sec, then, they are superimposed to make an averaged gray level uniform concentration image (UniC).

(4) The averaged concentration image (C_{avg})for each case is given by

$$C_{avg} = \frac{Tr_{avg} - Bk}{UniC - Bk} \qquad (1)$$

(5) Finally, C_{avg} is corrected to obtain normalized concentration C using concentration flux f_C of each experimental case. f_C is defined as

$$f_C = \int_0^h C_{avg} u dy \qquad (2)$$

, where, h is the building height shown in Fig.2 and u is x directional component of flow velocity.

3. Results and discussions

Experimental results for flow fields are shown in Fig.4~Fig.7. In all cases, straddling time is 8ms and sampling frequency is 1.85Hz. 100 instantaneous images were superimposed to obtain averaged vector images. In case 1 and case 2 shown in Fig.4 and Fig.5, large recirculating flows like a typical two-dimensional cavity flow are formed in the cavity area (zone above the road). However, because of the difference of the height of downstream roadside building, the recirculating flow area behind it is much larger in case2 than in case 1. The separated flow at the building edge reattaches at the point of about 80mm downstream position in case1, while the reattachment distance seems to be much longer in case 2 than that in case 1. This fact is important in the present study since the region behind the downstream building may be a significant zone for the concentration dispersion under the situation that natural wind is blowing across the road. Fig.6 is results for case 3. In this case, almost whole area

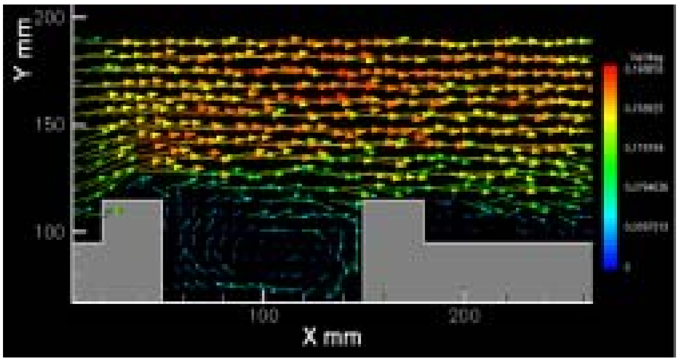

Fig.4 Velocity vectors, case 1.

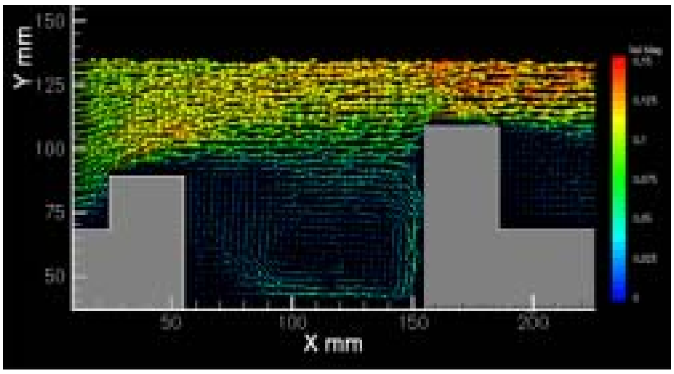

Fig.5 Velocity vectors, case 2.

of the test section are included in the wake of the upstream roadside building, therefore, turbulent intensity is higher than other cases both in the main flow and in the cavity flow as well as in the significant zone. Vector plot of case 4 is given in Fig.7. As a highway is supposed to be running above the road in the case 4, a complicated flow is observed in the cavity. Greater part of the separated flow at the front edge of the upstream roadside building flows downward through upper side of the highway and other part of it flows into the cavity and forms two recirculating zones, while the main flow and the flow in the significant zone behind the downstream roadside building shows similar tendency as those in the results of case 1.

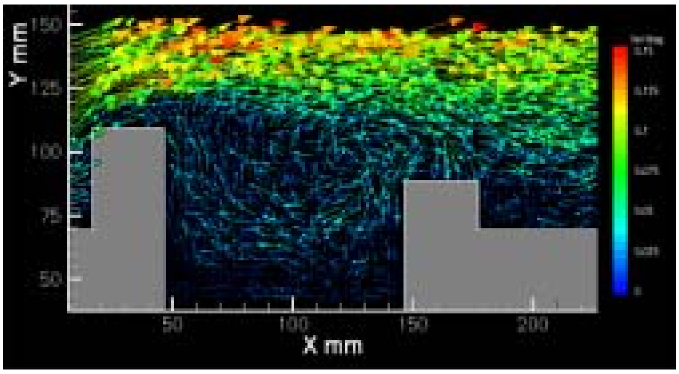

Fig.6 Velocity vectors, case 3.

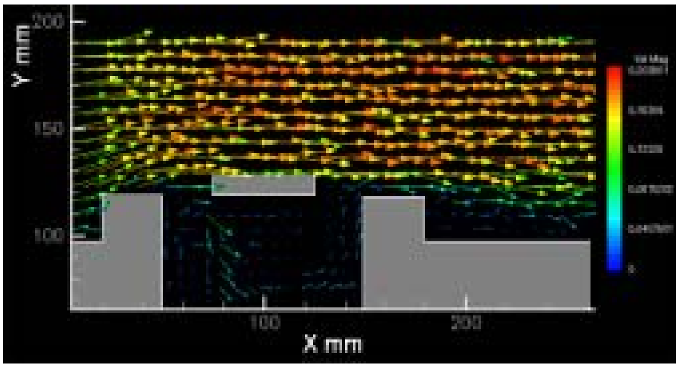

Fig.7 Velocity vectors, case 4.

Results for concentration field are given in Fig.8~Fig.11. The numerical values given on concentration contours of each figures are relatively normalized ones treated through the procedures described in **2.3.** All results are influenced by the flow properties mentioned above and show acceptable tendency. As for the concentration distributions in the cavity zones, although high concentration area is observed in the vicinity of the upstream roadside building because of the influence of the recirculating flow in all cases, result for case2 shows worse environment among the results for cases without highway and result for case 4 (Fig.11) shows worst one because of existence of the highway. As for the significant zone (area behind the downstream roadside building), the concentration disperses widely in case 2 and case 3 than other cases. This suggests that the height of the roadside building is one of the important factors to lower the risk of toxic substances in the down wind side environment.

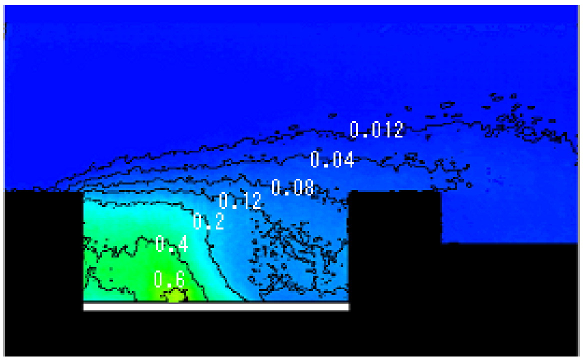

Fig.8 Concentration contours, case 1.

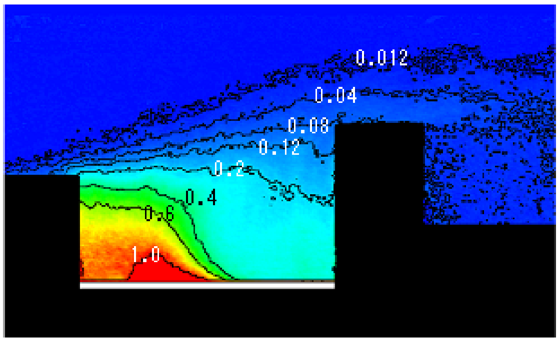

Fig.9 Concentration contours, case 2.

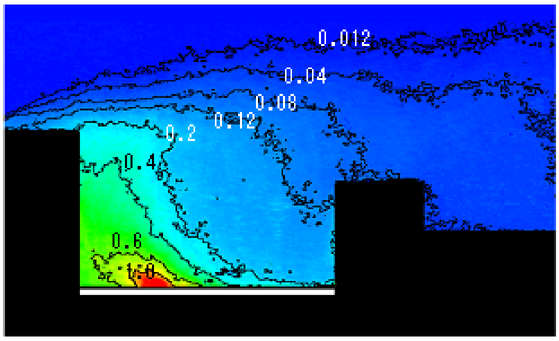

Fig.10 Concentration contours, case 3.

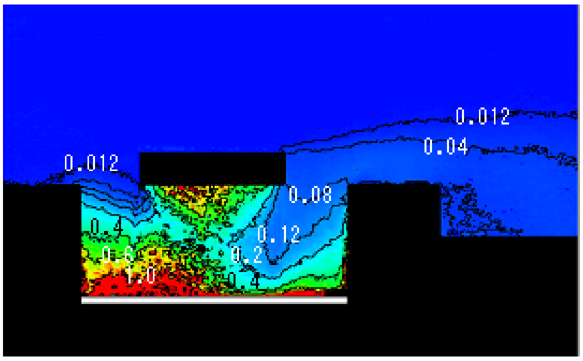

Fig.11 Concentration contours, case 4.

4. Conclusions

In order to prepare reliable experimental data, flow and concentration fields were measured using a scale model of a road with a simple roadside configuration. All measured data showed reasonable and acceptable tendency quantitatively. These data is rearranged and will be applied to validate various numerical models and to propose a reliable prediction method. That is our future study.

References

[1] Masuda A., Hajihara H., Nakanishi J., "*Continuous Monitoring of Benzene, NOx, CO in Atmosphere* ", *Bulletin of the Institute of Environmental Science and Technology, Yokohama National Univ*., Vol. 26, (2000), pp 23-37.

[2] Fushimi A., Hara C., Kawashima H., *"Continuous Monitoring for Air Pollutants and Long Term trend of benzene Level"*, *ibid*., Vol. 27, (2001), pp 9-23.

[3] U.S. EPA, "*Carcinogenic Effects of Benzene*", An Update EPA/600/P-97/001F, (1998).