China p 278

Experimental Study on Airflow in Underground Space of Metro System with a Constant Tracer-gas Injection Technique

Xiaofeng LI, Xianting LI, Yingxin ZHU
Department of Thermal Engineering, Tsinghua University
Beijing 100084, China

Abstract

A concept of mixing ratio of piston air is developed to evaluate the portion of the injecting air from tunnel mixed with the air in platform space of metro system. And a 3-dimensional turbulent model is used to simulate the airflow in metro platform resulted by the ventilation system and moving trains. Field measurement has been conducted to verify the 3-dimensional model. This experiment is performed during the normal operation time of a metro station with constant tracer-gas injection method. The results agree well with the numerical solution. The reason of the differences between experiment and simulation is discussed. It is concluded that the model is accurate enough for HVAC system design of metro line.

Introduction

The airflow in platform is important in thermal environment control system design for metro system. It is because piston air injected from tunnel to platform is one of the most important factors deciding (1) the cooling load of platform space, (2) the effeciency of ventilation system in platform, (3) the indoor air quality of platform space. The so called 'piston air' is the air from the tunnel induced by the piston action of the moving train. The piston air from the tunnel is usually polluted and heated by the train braking.

The air in platform space will fully mix with the injected air from tunnel if the injected air moves at very low speed. However, the air from the tunnel is flowing at average speed about 1~3 m/s and maximum 8~10 m/s [1], there must be a part of air leaving the platform before mixing. From the view of thermal environment control, the polluted and heated piston air is different from the air in platform space. One of the tasks of the ventilation or air-conditioning system is to prevent the piston air from effecting the platform environment.

Therefore, 'mixing ratio' is developed to evaluate quantitatively the portion of the piston air mixed with the air in platform space[2]. The concept 'mixing ratio' is defined as the percentage of the piston air which is mixed with the platform air over the total amount of piston air. If the quantities of the piston air in both the inlets and outlets are known , the mixing ratio of the piston air can be calculated.

A generic control volume for studying airflow in platform is shown in Figure 1. The metro station shown in Figure 1 is a typical one in current metro lines in China. The train moves in the direction of the arrow, and the ventilation system exhausts air from the grills under the platform. So the mixing ratio of piston air is presented as:

$$\eta_{mix} = 1 - \frac{G_{pa,outlet1} + G_{pa,exhaust1}}{G_{pa,inlet1}} \qquad (1)$$

Where $G_{pa,inlet1}$, $G_{pa,outlet1}$ and $G_{pa,exhaust1}$ are the mass flow rate of piston air in different passages; the subscript 'pa' means piston air.

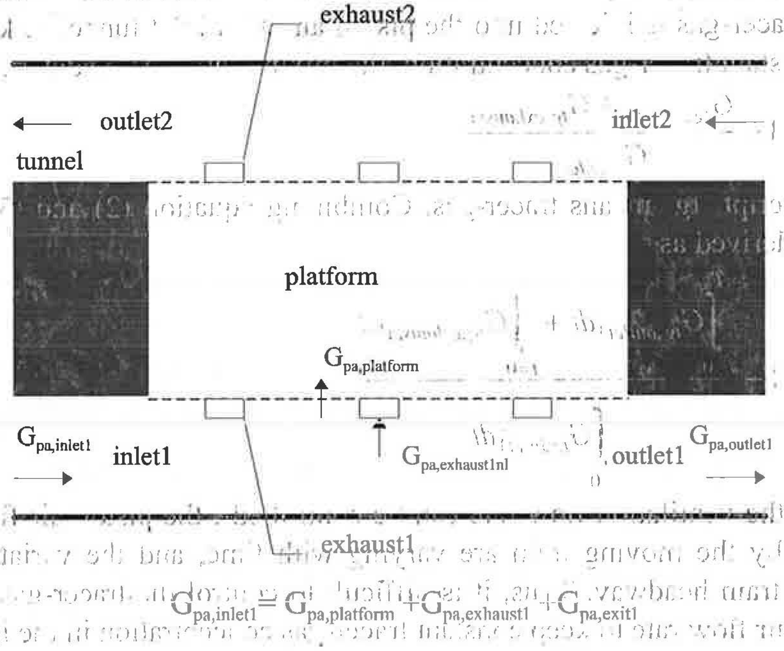


Figure1 A generic control volume for studying airflow in platform

Since the flow rate of piston air varies periodically with the headway of the train, the mixing ratio should be determined by integrating over a period of T to get an average,

$$\bar{\eta}_{mix} = \frac{\int_{t=0}^{T} G_{pa,inlet1}\eta_{mix}dt}{\int_{t=0}^{T} G_{pa,inlet1}dt} \qquad (2)$$

To determine the mixing ratios of piston air of different stations in HVAC system design for a metro line, a 3-dimentional numerical model is used to simulate the field of the station. With the simulation results, average mixing ratio of piston air can be calculated. The reliability of the model should be verified by experiment. Examination should be made for some factors such as the grid and the boundary conditions by comparing the simulation results and the experiment data. Therefore the field measurement with tracer gas technique to verified the 3-dimensional model is performed.

Experiments

Fundamental

The tracer-gas technique is always used to study the airflow within the buildings[3]. Constant concentration method and decay method are usually used in this case. However, the experiment for studying the effect of piston air on the airflow in platform of metro system should be performed during the normal operation time. Different from common buildings, a typical metro platform is a large and semi-opened space because there are at least four tunnel ends and several passenger's entrances connected to an island type platform as shown in Figure 1, so it is difficult to keep the constant initial tracer-gas concentration before decaying. It means the decay method is not available here.

When tracer-gas is injected into the piston air at an inlet tunnel to keep the piston air having a constant tracer-gas concentration, the mixing ratio can be determined as:

$$\eta_{mix} = 1 - \frac{G_{tg,outlet1} + G_{tg,exhaust1}}{G_{tg,inlet1}} \tag{3}$$

Where the subscript 'tg' means tracer-gas. Combining equation (2) and (3), the average mixing ratio is derived as

$$\overline{\eta}_{mix} = 1 - \frac{\int_{t=0}^{T} G_{tg,outlet1}dt + \int_{t=0}^{T} G_{tg,exhaust1}dt}{\int_{t=0}^{T} G_{tg,inlet1}dt} \tag{4}$$

Although the ventilation flow rate can be controlled, the piston air-flow rates from tunnels caused by the moving train are varying with time, and the variation frequency depends on the train headway. Thus, it is difficult to control the tracer-gas injecting rate with the piston air flow rate to keep constant tracer-gas concentration in the inlet tunnel.

Therefore, the most possible way to measure the airflow in the metro platform is constant tracer-gas injection method. When tracer-gas with constant injection rate is injected into the piston air in an inlet tunnel, The mixing ratio can be obtained from equation(3):

$$\eta_{mix} = 1 - \frac{G_{tg,outlet1} + G_{tg,exhaust1}}{\rho_{tg,inlet1}F} \tag{5}$$

Where F is the volumetric tracer-gas injection rate, $\rho_{tg,inlet1}$ is tracer-gas density. From the equations (5) and (2), the average mixing ratio is derived as

$$\overline{\eta}_{mix} = 1 - \frac{\int_{t=0}^{T} G_{pa,inlet1}G_{tg,outlet1}dt + \int_{t=0}^{T} G_{pa,inlet}G_{tg,exhaust1}dt}{\rho_{tg,inlet1}F \cdot \int_{t=0}^{T} G_{pa,inlet1}dt} \tag{6}$$

Where

$$G_{pa} = \iint_{A} \rho_{pa}udA \tag{7}$$

$$G_{tg} = \iint_{A} \rho_{tg}cudA \tag{8}$$

Where c is the tracer-gas concentration. Assuming that the velocity and tracer-gas concentration is uniform in the cross-section, then

$$G_{pa} = \rho_{pa}\bar{u}A \tag{9}$$

$$G_{tg} = \rho_{tg}\bar{c}\bar{u}A \tag{10}$$

Assuming the density of air and tracer-gas can be considered constant, Equation(6) can be shown as

$$\eta_{mix} = 1 - \frac{A_{outlet1}\left(\int_{t=0}^{T} \overline{u}_{inlet1}\overline{u}_{outlet1}\overline{c}_{outlet1}\,dt + \int_{t=0}^{T} \overline{u}_{inlet1}\overline{u}_{exhaust1}\overline{c}_{exhaust1}\,dt\right)}{F \cdot \int_{t=0}^{T} \overline{u}_{inlet1}\,dt} \tag{11}$$

Since the platform space is quite large (above 8000 m^3), the experiment time needs to be well designed to get a steady concentration variation process of tracer-gas. In such a large space with high air flow rate (the average higher than 100,000m^3/hr), a on site experiment is a money-cost work, so the experiment scheme must be designed very carefully to avoid all interference that may lead the experiment to fail.

Station and metro system

The testing section is a medium-sized station of the metro line in Shanghai, China (see Figure 2). The platform is about 140 meters long , 16.8 meters wide and 5.4 meters high. There are four tunnels at the end of the station and four passenger's entrances in the platform. The passenger's entrances connects directly to the ticket hall upstairs. The area of cross- section of the tunnels is 5.4×4.2m. At one end of platform, there is a stuff's path connecting two tunnels about 1.8 meters wide and 4.0 meters high. The piston air from one tunnel can flow through the path to the tunnel in the other side. The train runs from 5:00am to 11:00pm with headway of 9 minutes. The ventilation system is shut down during the experiment because in summer case, during the cooling period, the ventilation system is usually switched to 'off'. Compared with the ventilation case, the cooling case is a relative simple one for studying the platform airflow.

Tracer gas and apparatus

To trace the dynamic process of the piston air, the concentration of the tracer-gas has to be sampled and recorded continuously. Since the experiment is conducted during the normal operating time, the tracer-gas should be nontoxic and safe. Due to the huge volume of the platform space, the tracer-gas should be released at a relative low concentration.

Thin methane (CH_4 of 0.5%) is selected as the tracer-gas. It meets the requirements of safety. A 08-B infrared gas analyzer is used to measure the concentration. Such a gas analyzer can measure continuously the concentration of methane below 100ppm. It was calibrated before and after the experiment using natural air and standard gas of 95ppm CH_4. The accuracy of analysis is 1% of full scale, i.e., 1ppm.

The velocity of the airflow at each tunnel is tested continuously by auto-recording hot-bulb anemometers. The accuracy of the hot-bulb anemometers is estimated about 5%. The measured data are recorded in the micro-computer based recording sets sized as cigarette boxs.

Procedure

During this experiment, the tracer-gas was injected at one end of the upstream tunnel with a constant injecting rate. The sampling point was located at the end of downstream tunnel, the same side of the platform as the one in which the tracer-gas was injected. The velocity of airflow at the ends of four tunnel is measured simultaneously by eight auto-record anemometers. At each cross-section of the tunnel, two anemometers was placed.

One of the test points was about 2.8 meters high from the track, while the other one was set at the level of the platform. Both were 0.8m away from the tunnel wall. Figure 2 shows the exact position.

The concentration and injecting rate is predicted before the measurements. The dynamic flow rate of piston air was simulated by means of STESS, a Subway Thermal Environment Simulation Software developed by Thermal Engineer Department of Tsinghua University[4]. The simulation results is used to predict the rate that the tracer-gas should be injected at to acquire the suitable concentrations of tracer-gas in the downstream tunnel to prevent from too low or too high concentration to be measured there. The total volume of methane was strictly limited for the sake of safety, hence, the rate of injecting has to be kept at a relatively low value. The experiment is performed twice. In the first experiment, the equivalent injection rate of pure methane was 1.80 m^3/h, and in the second one, the equivalent injection rate was 2.20 m^3/h.

The infrared analyzer was placed at the stuff's path near to the sampling point. The concentration of the tracer-gas was measured every five seconds.

Base on the simulation results, the average air velocity over time in the tunnel is more than 1.56m/s. The equivalent diameter of the tunnel is determined as the ratio of four times area and perimeter. Therefore, the Reynolds number of the tube flow is:

$$Re = \frac{Vd}{\nu} = \frac{1.56 \times 4.7}{1.6 \times 10^{-5}} = 4.6 \times 10^5 \qquad (12)$$

The result shows that the air flow pattern in the metro tunnel is in turbulent rough zone in which the air velocity in a cross-section should be uniform. Even though, the test point of velocity is set 0.8m away from the tunnel wall to get rid of the possible effect of laminar boundary layer. The system error induced by the inequality of velocity in the cross-section is estimated at most about 20%. The flow rate of piston air of each time point can be obtained by multiplying the air velocity and the area of the tunnel cross-section. Consequently, the error of the flow rate is estimated about 20%.

The experiments lasted about half an hour until all the tracer-gas went way. The data was input in a computer to be processed.

Results and analyse

The average velocities of airflow in the four tunnels is obtained from the average of the two anemometers' data. It was given at Figure 3 and Figure 5. The concentrations of the tracer-gas at the sampling point of the two experiments are shown at Figure 4 and Figure 6.

Because the differences between the two series of measured data are very small (less than 0.5m/s or 5%), the air velocities in the same cross-section can be though uniform. It is identical to the theory analysis. Therefore, the mean values of the measured data of the two anemometers in the same test cross-section is though reasonable enough to be used as the mean velocity of the cross-section in equation (11).

However, the uniformity does not present in the measured result of tracer-gas concentration. The concentration varied significantly with the position in the same cross-section. This may be explained by the effect of the platform structure. At one end of the platform, there is a stuff's path near the testing point. The piston air from the other tunnel may go directly through the path and, consequently, dilute the tracer-gas in this area while the tracer-gas away from the path keeps the higher concentration. It is difficult to get the average concentration of a cross-section of the tunnel, because it is impossible to set enough amount of sampling points in the operating metro tunnel for the sake of safety.

Based on the discussion above, it is found that it is not enough for deriving the mixing ratio of piston air quantitatively only based on the field measured data. Therefore, the detail analyse of the airflow in platform must be based on 3-dimensional simulation. The significant of the field experiment is to get the air velocity in tunnels and the tracer-gas concentration of a point in the tunnel. These data are used in model validation first, then to derive the mixing ratio of piston air from the validated simulation results. The validation process is to use the average velocities of the four tunnel acquired from field measurement as the boundary condition of the model, and compare the concentrations of tracer-gas obtained from the experiments with the simulation results to verified the model.

Mathematical model

The governing equations

The process of airflow in a platform is 3-dimensional time-dependent problem. The mixing of the piston air and air in platform is turbulent process. Because there is little different between the temperature of piston air and which of the air in platform, the effect of the buoyancy can be ignored. The temperature of air in platform can be think as constant.

Therefore, the governing equations are consisted of continuity, momentum, species, kinetic energy and its dissipation. All these equations can be written in the general form:

$$\frac{\partial}{\partial t}(\rho\varphi) + div(\rho \vec{u} \varphi + \vec{J}_{\varphi}) = S_{\varphi} \qquad (13)$$

where φ stands for a general fluid property such as u, v, w, etc. and ρ, $\vec{u}$, $\vec{J}_{\varphi}$, S_{φ} are density, velocity vector, diffusive-flux vector and source rate per unit volume, respectively.

The diffusive flux is given by:

$$\vec{J}_{\varphi} = -\Gamma_{\varphi}\, grad\varphi \qquad (14)$$

where Γ_{φ} denotes the effective exchange coefficient of φ.

The values of φ, Γ_{φ} and S_{φ} are listed in Table 1.

Table 1 Values of φ, Γ_{φ} and S_{φ}

φ	Γ_{φ}	S_{φ}
1	0	0
u	μ_{eff}	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu_{eff}\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu_{eff}\frac{\partial v}{\partial x}) + \frac{\partial}{\partial z}(\mu_{eff}\frac{\partial w}{\partial x}) + g_x(\rho - \rho_{ref})$
v	μ_{eff}	$-\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\mu_{eff}\frac{\partial u}{\partial y}) + \frac{\partial}{\partial y}(\mu_{eff}\frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(\mu_{eff}\frac{\partial w}{\partial y}) + g_y(\rho - \rho_{ref})$
w	μ_{eff}	$-\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}(\mu_{eff}\frac{\partial u}{\partial z}) + \frac{\partial}{\partial y}(\mu_{eff}\frac{\partial v}{\partial z}) + \frac{\partial}{\partial z}(\mu_{eff}\frac{\partial w}{\partial z}) + g_z(\rho - \rho_{ref})$
k	$\frac{\mu_{eff}}{\sigma_k}$	$G_k + G_b - \rho\varepsilon$
ε	$\frac{\mu_{eff}}{\sigma_\varepsilon}$	$\frac{\varepsilon}{k}[(G_k + G_b)C_1 - C_2\rho\varepsilon]$

c	$\frac{\mu_{eff}}{\sigma_c}$	0
$\mu_{eff} = \mu_l + \mu_t, \mu_t = C_D \rho k^2 / \varepsilon$		
$G_k = \mu_t \{2[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2 + (\frac{\partial w}{\partial z})^2] + (\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x})^2 + (\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z})^2 + (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2\}$		
$G_b = \mu_t \frac{g}{\rho} \frac{\partial \rho}{\partial y}$		
$C_1 = 1.44, C_2 = 1.92, C_D = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3, \sigma_c = 1.0$		

Boundary condition

There are three kinds of boundary conditions: solid wall, inlet and outlet. For solid wall, non-slip condition and wall-functions are used. The velocities and tracer-gas concentration at the inlets are obtained from the experiments. The first order derivations of parameter φ at the outlets (φ=u, v, w, k, c) are assumed as 0.

Method to solve the mathematical model

All the equations in general form are non-linear partial differential equations and coupled each other. SIMPLE algorithm is used to get numerical result. The detail about SIMPLE can be seen in reference [5].

Comparison and analysis

The result of simulation is compared with the experiment data (Figure 4 and 6) and it shows great coincidence. And the discrepancy will decrease apparently with grids applied get finer. The differences are still within the range of system error of the measurements Therefore, the grids is reasonable to be used to evaluate the mixing ratio in practical application.

The mixing ratio obtained from the validated simulation is 26%. The mixing ratio on other cases such as the ventilation case or cooling cases of different platform configration can also be determined by the validated simulation model.

Conclusion

The concept of mixing ratio has been proposed in this paper to quantitatively analyze the effect of piston air on the environment of platform of metro. It may serve as a useful index in improving the ventilation system and as tool for predicting the cooling load of metro more accurately. Although the experiment cannot lead directly to the mixing ratio, it can be used to evaluated the reliability of the 3-dimensional model. With the 3-dimensional numerical simulation, the percentage of the piston air mixed with platform air under different operation cases can be determined.

The mixing ratio of piston air has been used in several HVAC project of metro systems in China to predict cooling load and conduct technique economy analyses.

Reference

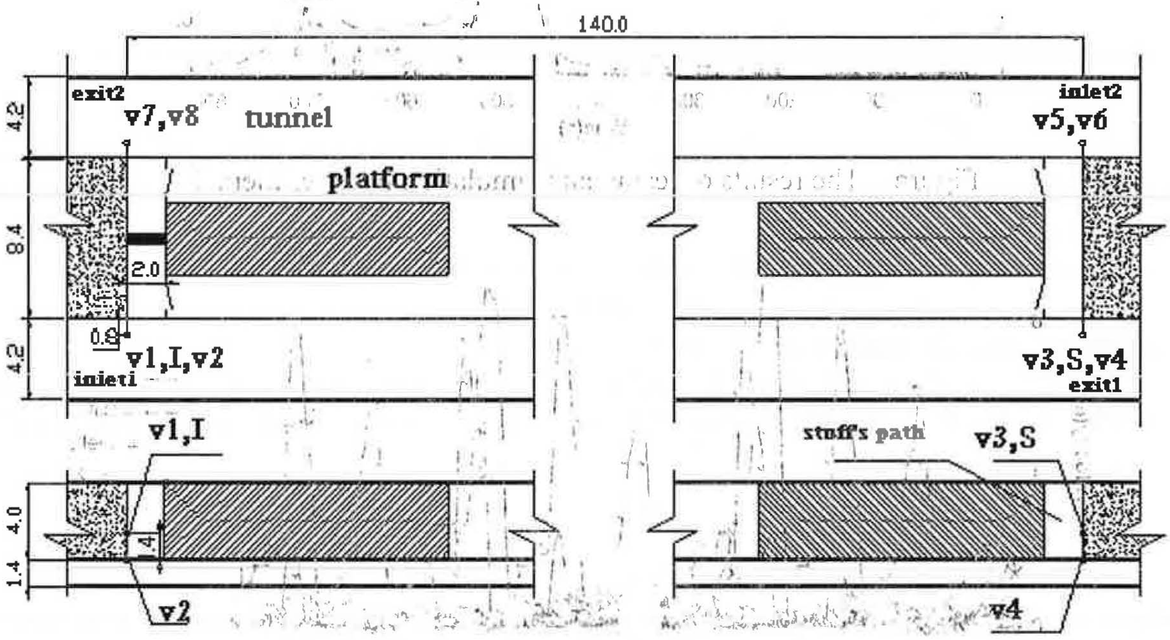
[1] Department of Thermal Engineer, Tsinghua University, 'The measurements and analysis of thermal environment of Beijing subway system', June,1982

[2] Xianting LI, 'The application of CFD method in HVAC', Master degree thesis of Tsinghua Univesity, 1993

[3] P.Lagus and A.K.Persily, 'A review of tracer-gas techniques for measuring airflows in buildings', ASHRAE Transaction, HI-85-22 No.1, 1985

[4] Department of Thermal Engineer, Tsinghua University, 'STESS—A Subway Thermal Environment Simulation Software, Users' manual',1996

[5] Patankar, S.V, 'Numerical heat tranfer and fluid flow', McGraw-Hill, New York,1979



v1—v8 , the test points of velocity

I , the point of tracer-gas injection

S, the sampling point of tracer-gas concentration

Figure 2 the locations of the measuring points in the station of the subway

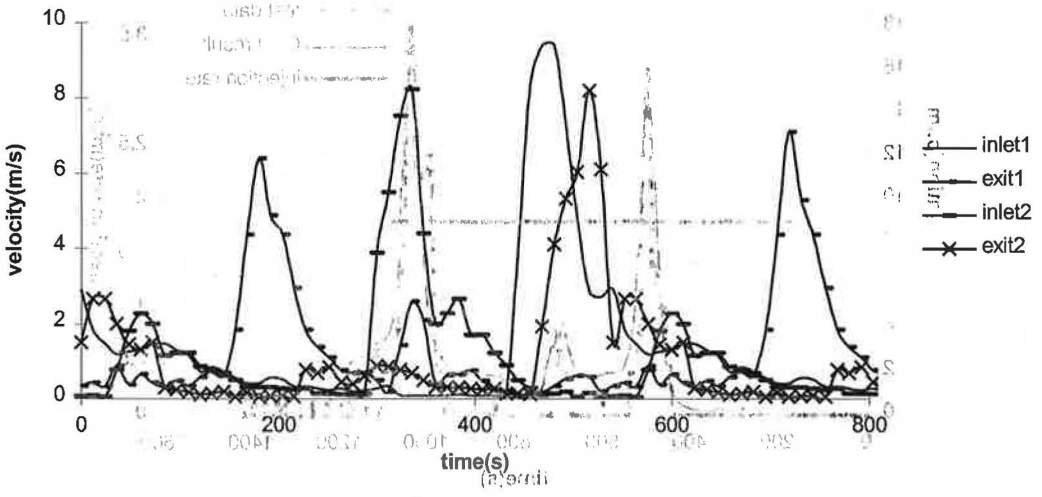


Figure 3 The velocity in four tunnel in experiment1

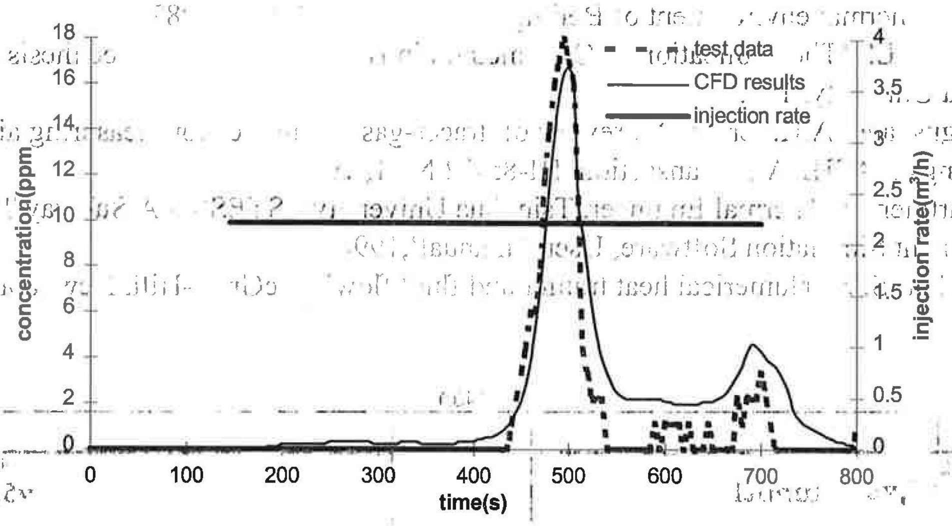


Figure 4 The results of tesing and simulation in experiment 1

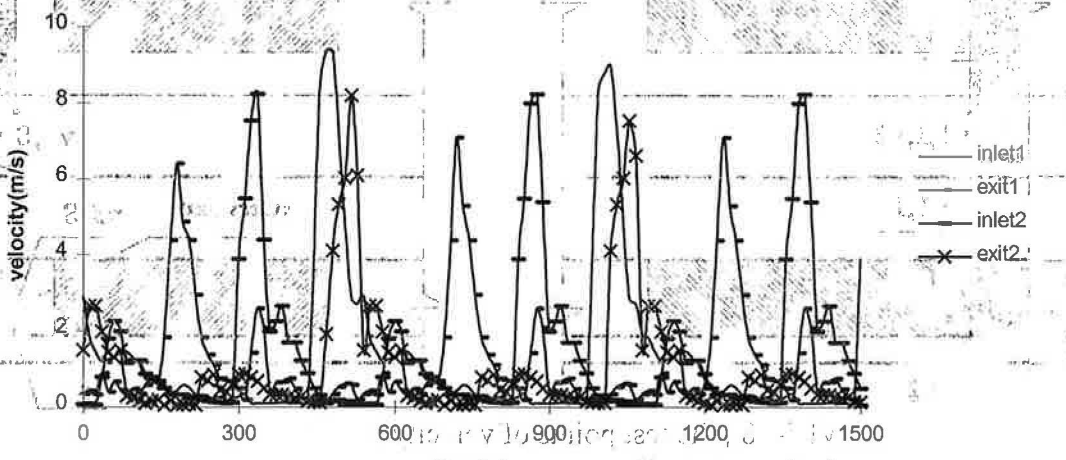


Figure 5 The velocity in four tunnel in experiment 2

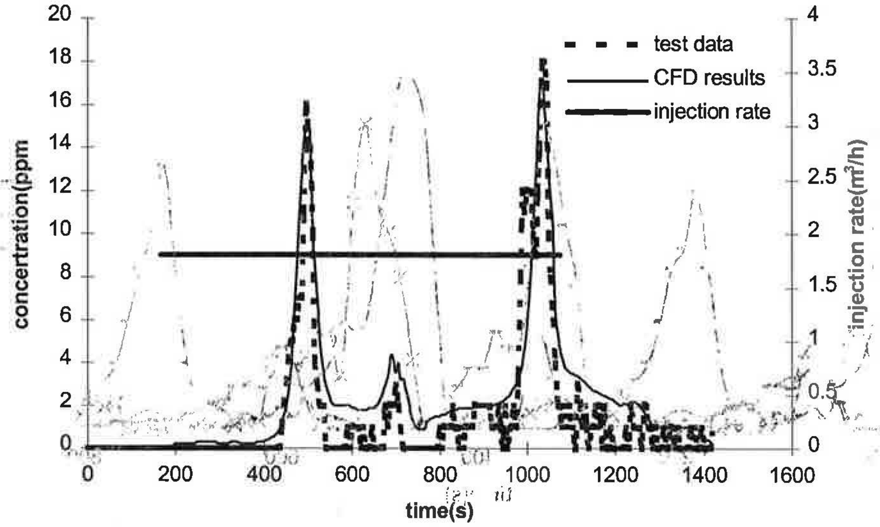


Figure 6 The results of tesing and simulation in experiment 2