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# Flow Field Analysis of Smoke in a Rectangular Tunnel

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**Abstract** : In order to simulate a smoke or poisonous gas emergency in a rectangular tunnel and to investigate a better way to exhaust the smoke, the characteristics of smoke flow have been analyzed using flow field data acquired by Particle Image Velocimetry(PIV). Olive oil has been used as tracer particles with the kinematic viscosity of air, $1.51\times10^{-5}$ $m^2/s$. The investigation has done in the range of Reynolds number of 1600 to 5333 due to the inlet velocities of 0.3 m/s to 1 m/s respectively. The average velocity vector and instantaneous kinematic energy fields with respect to the three different Reynolds numbers are comparatively discussed by the Flow Manager. In general, the smoke flow becomes more disorderly and turbulent with the increase of Reynolds number. Kinematic energy in the measured region increases with the increase of Reynolds number while decreasing at the leeward direction about the outlet region.

**Key words** : PIV, Reynolds number, Mean velocity vector field, Vorticity, Flow Manager

## 1. Introduction

Underground constructions like railroad tunnels, highway tunnels, subways are necessary to be designed for smoke or poisonous gas emergency according to the social and economical development now. During those emergencies in a rectangular tunnel or inside a long corridor, it will cause a extreme damage and threaten the people′s lives. In this study, smoke flow characteristics have been observed at different inlet speeds on the floor of a straight channel by using the PIV (Particle image velocimetry).

A turbulent flow in a rectangular tunnel is an active area of research because of its wide practical applications to heat exchanger tube bundles, to smoke exhaust devices, and to cooling systems for nuclear power plants[1]. So there has been a considerable amount of theoretical and experimental work committed to the studies of different aspects of flow in rectangular tunnels or tube bundles.

The study of the turbulent flow field in a rectangular tunnel has been carried out by many investigators in the past. Pan and Acrivos measured the steady flows in rectangular cavities in 1967[2] and Aiba et al.(1982) observed a mean and turbulent intensity measurement in inline and

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staggered tube bundles using a two-component hot-wire anemometer when the pitch ratio were arranged from 1.2 to 1.6 and the Reynolds number was 30000[3]. Kim et al. performed flow visualization in rectangular ducts (duct aspect ratios were 1/2 and 1/5)[4] and Bonhoff et al. investigated experimentally and numerically the flow field in a square channel with 45 degree ribs at a Reynolds number of 50000[5].

In this study, particle image velocimetry (PIV) is used to investigate the characteristics of the flow structure in a rectangular tunnel when changing the Reynolds numbers. Particle image velocimetry (PIV) is the newest entrant to the field of fluid flow measurement and provides instantaneous velocity fields over global domains. As the name suggests, PIV records the position over time of small tracer particles introduced into the flow to extract the local fluid velocity[6]. Thus, PIV represents a quantitative extension of the qualitative flow-visualization techniques that have been practised for several decades. PIV is a whole-flow-field technique and can provide instantaneous velocity vector measurements in a cross-section of a flow. It is a non-intrusive optical method and is possible to obtain instantaneous velocity maps in a flow plane of interest. After post-processing, the mean velocity fields and instantaneous or average vorticity fields can be obtained. The basic requirements for a PIV system are an optically transparent test-section, an illuminating light source (laser), a recording medium (film, CCD, or holographic plate), and a computer for image processing.

This paper presents the experimental results of air flow characteristics in the rectangular tunnel at three different Reynolds numbers: velocity field, streamline field, and instantaneous kinematic energy field. The main objective of this paper is to analyze air flow characteristics in a rectangular tunnel by PIV and to help provide an evacuation path from the smoke or poisonous gas.

## 2. Experiment

The experimental equipments are made up of four basic components: (1) An optically transparent test-section containing the flow seeded with tracer particles; (2) A light source (laser) to illuminate the region of interest (plane or volume); (3) Recording hardware consisting of either a CCD camera or film, or holographic plates; (4) A computer with suitable softwares to process the recorded images and extract the velocity information from the tracer particle positions. The experimental equipments are shown in Fig. 1.

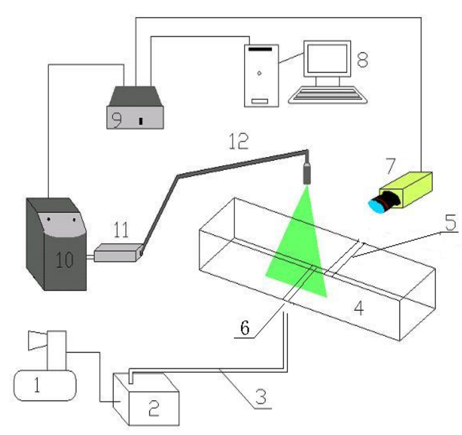



**Fig. 1 A schematic of experimental equipments**

1. Compressor 2. Atomizer
3. Inlet Tube 4. Tunnel model
5. Outlet 6. Inlet
7. CCD Camera
8. Host Computer & Software
9. System Hub
10. Operating Device of Nd-YAG Laser
11. Nd-Yag Laser 12. Mirror Arm

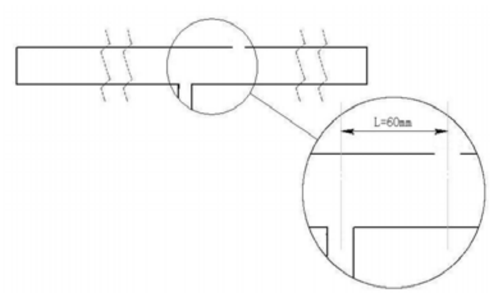



**Fig. 2 Test section of the experiment**

The transparent acrylic rectangular tunnel of the test section is presented in Fig. 2. The tunnel used in the modeling is 800 mm long, 80 mm high, and 80 mm wide. As shown in Fig. 2, the inlet is positioned in the middle of the tunnel bottom, while the outlet is located at the distance 60 mm on the right side away from the center of the tunnel ceiling. Tracer particles of olive oil pressurized and transported by an air compressor enter the rectangular tunnel through the plastic-pipe inlet and then exit through the upper outlet. In order to get the appropriate flow speeds, a plastic-trunk is used to get specific lower speeds and a small axial flow fan is installed to provide three different uniform flow speeds. Each image is captured by the CCD camera which is positioned at the right angle to the light-sheet using the Dantec PIV 2000 system and it is formatted by bmp files. And each image corresponds to two pictures; one picture A taken at time T and the other picture B taken at time T+Dt (Dt depends on the time between pulse). Then the pictures are inputted into the PIV processor software called the Flow Manager.

In this software, for reasons of experimental reproducibility, the raw vector maps are archived and the validated vector maps are output. Further analysis can produce streamlines, vorticity, and so on.

## 3. Results and Discussions

The experimental flow is an atomizing smoke from the atomizer in order to control and change the three different speeds in this experiment. The smoke flow characteristics in the tunnel have been researched at three different Reynolds numbers. In the previous paper[7], the inlet velocities, the flow rates, and the distance between inlet and outlet is constant. Therefore, three different Reynolds numbers are given in this paper. Olive oil has been used as the tracer particles and the kinematic viscosity of air is 1.51 x $10^{-5}$ $m^2/s$. The average velocity vector field and those streamlines, and the instantaneous kinematic energy are discussed in the paper.

### 3.1 The average velocity vector graph

The smoke flow characteristics have been experimented at three conditions of olive oil flow rates of $Q_1$ = 1.3 $m^3/h$, $Q_2$ =

2.8 $m^3/h$, $Q_3$ = 4.95 $m^3/h$ and velocities of $V_1$ = 0.3 m/s, $V_2$ = 0.6 m/s and $V_3$ = 1 m/s respectively. In Figures 3 to 5, mean velocity vector fields are shown depending on the three different Reynolds numbers, $Re_1$ = 1600, $Re_2$ = 3200 and $Re_3$ = 5333. In order to show the flow velocity fields at the inlet and outlet, a cross-sectional image of 145mm x 80mm area has been examined by using PIV. Inlet realm is located at the distance, 40 to 60 mm, from the left part of the floor in the x-y plane, and outlet realm is at 100 to 120 mm on the right side away from the inlet position at y = 80 mm. According to the variation of the Reynolds number, the following can be concluded from the average velocity vector graph. In the inlet region, the smoke produced by the Atomizer flows upwards.

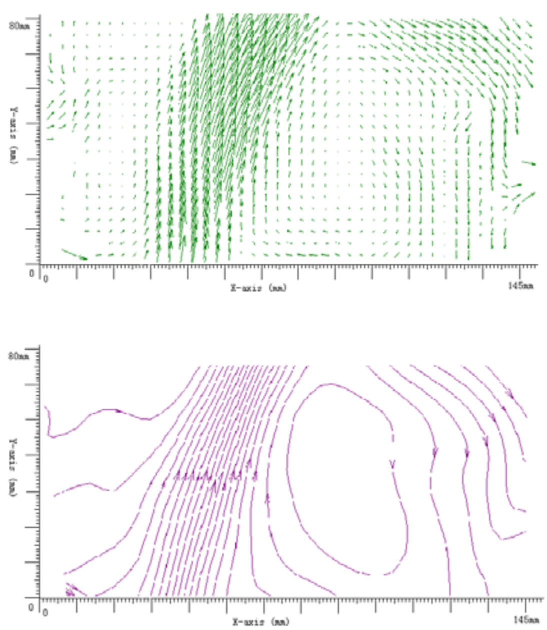



**Fig. 3 Mean velocity vector field and streamlines using PIV when Re=1600**

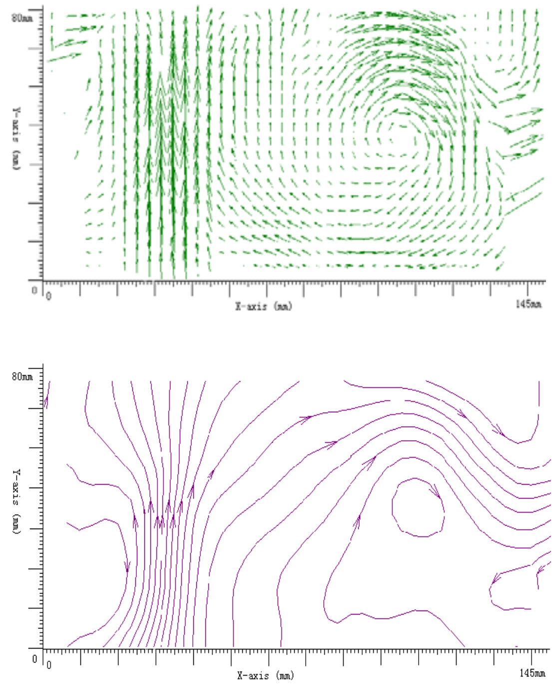



**Fig. 4 Mean velocity vector field and streamlines using PIV when Re=3200**

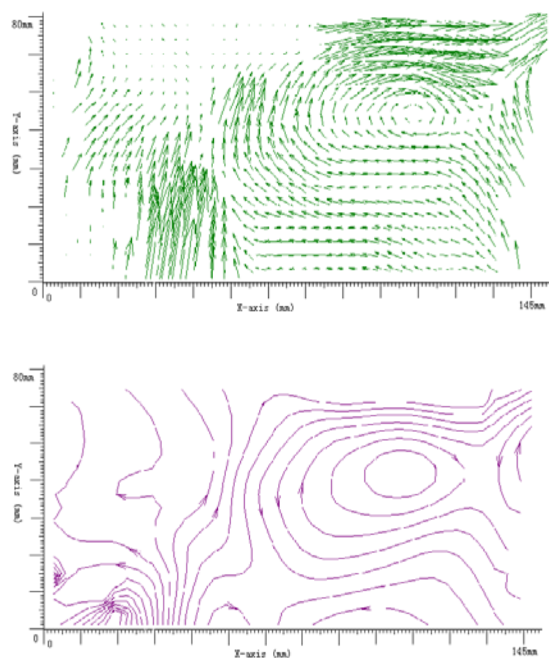



**Fig. 5 Mean velocity vector field and streamlines using PIV when Re=5333**

When the Reynolds number is 1600, as shown in Fig. 3, the vortex is being produced from smoke in the windward region of inlet position because of the impact of the tunnel wall. At the same time, one large circumfluence is found at the region below between the inlet and outlet in the tunnel. This implies that some part of flow along the ceiling layer is exhausted into the outlet and the rest of the flow goes towards inside the tunnel. It is also observed that the maximum value of mean velocity occurs in the inlet and outlet region. And the mean velocity value is lower at the downside region than that at the near inlet and outlet region. It is helpful to make a decision of the emission of smoke and the escape of endangered people to the leeward direction.

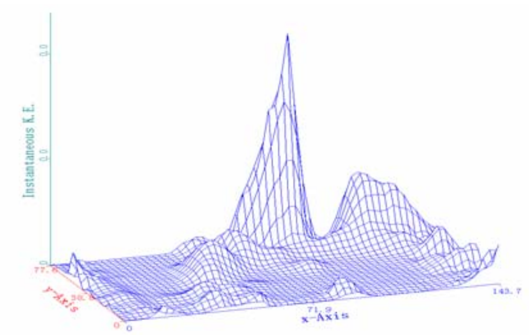
When the Reynolds number increases to 3200, as shown in Fig. 3, the flow velocity of the smoke at the top of the tunnel is significantly larger than that of the bottom. Increasing the longitudinal smoke velocity makes the smoke spread to the leeward direction. The vortex which is found near the middle layer of the tunnel just below the exhaust outlet is more active.

When the Reynolds number increases up to 5333, as show in Fig. 5, some vortices form at the upper part of the tunnel near the outlet region and other parts. As the inlet flow velocity increases, the flow velocity of smoke in the top of the tunnel has been greatly improved and the smoke emission velocity has also increased. Comparing with the Reynolds number of 3200, the smoke flow condition due to the exhaust outlet in the leeward direction from a practical point of view on the floor does not have significant change. With the increase of Reynolds numbers, the movement of the fluid is more disorderly and the region of finite circulation is subjected to the inlet flowing velocities.

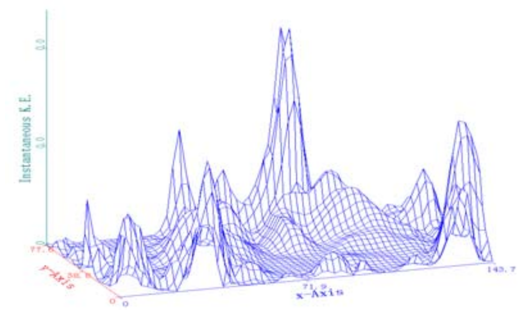
### 3.2 Instantaneous Kinematic Energy Field

The experimental results here describe the instantaneous kinematic energy fields in the 145 mm x 80 mm area of the rectangular tunnel by changing the Reynolds numbers as in Fig. 6. The exhaust outlet is installed at 60 mm away from the ceiling of the inlet position.

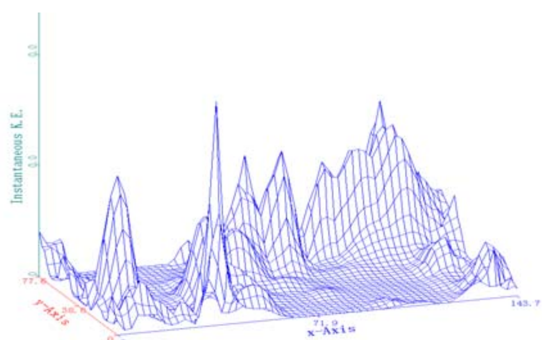
As shown in Fig. 6(a), the highest value of kinematic energy is distributed near the outlet region in case that the Reynolds number is low as 1600, regardless of the whole low value. As the Reynolds number increases in Fig. 6(b), the kinematic energy increases in disorder. The peak energy value is the same as that of the lower Reynolds number of 1600. As the Reynolds number is 5333 as shown in Fig. 6(c), however, the bulk of considerably high kinematic energy spreads widely past the outlet region. With the increase of Reynolds numbers, the kinematic energy increases. In addition, the kinematic energy distribution is covered in a wide range of the tunnel at high Reynolds numbers. It is considered that the ceiling rectangular opening has an effect on the exhaust system in the fire tunnel[8]. These results show that an appropriate ventilation or opening must be maintained to provide the endangered people with an evacuation way with each of Reynolds number.




(a) Re=1600




(b) Re=3200




(c) Re=5333

**Fig. 6 Instantaneous kinematic energy plots for various Reynolds numbers by PIV**

## 5. Conclusions

An experimental study based on three different Reynolds numbers has investigated the velocity vector fields with the streamlines and the instantaneous kinematic energy fields in the rectangular tunnel, the following conclusions can be pointed out:

(1) The flow analyses are shown the better way to exhaust the smoke through the experimental methods by using the PIV technology consisted in an ensemble average of the instantaneous PIV acquisitions.

(2) As the Reynolds number increases, the behavior of fluid movement becomes more turbulent and significantly magnifies the diffusion and emission of smoke. It is shown that in this study what the definition of the Reynolds number means definitely.

(3) There is a critical velocity in such a particular condition in the tunnel flow. Circumfluent flow occurs inside a rectangular tunnel when the flow velocity is greater than the critical velocity. As the flow velocity increases over the critical velocity, it causes more circumfluence in the recirculation zone and becomes more active. The results are similar to those of V. P. Kolgan and A. S. Fonarev[9].

(4) With the increase of Reynolds numbers, the kinematic energy increases. It is considered that the ceiling rectangular opening has an effect on the exhaust system in the tunnel. These results show that an appropriate ventilation or opening must be maintained to provide the endangered people with an evacuation way with each of Reynolds number. Finally, flow velocity distribution

and vortex structures have been properly summarized by the experimental analyses and the image processing. Some new phenomena such as turbulence intensity and vorticity were found. They will be reference data for further investigations.

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