Wind tunnel experiments on smoke diffusion from a chimney

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Abstract. The diffusion of heated and unheated jets from a chimney was investigated in cross flows with large-scale turbulence generated by a Makita-type active turbulence generator and with grid generated turbulence. The behavior of jet with smoke was observed by a high-speed camera. The smoke was dispersed more widely by meandering motion in the large-scale turbulence. The turbulent eddies corresponding to the integral scale should effectively contribute to the meandering smoke diffusion. The time-averaged smoke concentration distribution was obtained from the brightness values of instantaneous images. The stream-wise variations of the smoke diffusion width and the smoke flow center were evaluated from the distribution. Obtained data were compared with previous correlations.

1. Introduction

Air pollution and deposition of aerosol particles (PM2.5, PM10) caused by industrial plants, motor vehicle, ordinary houses where coal is used for heating apparatus, etc., seriously affect to ecosystems and human health. There are the several millions of people dying annually owing to the atmospheric pollution. Consequently, there is an increasingly high demand for a more precise assessment of particle diffusion, e.g., the diffusion of PM2.5, to mitigate air pollution problems. Due to increasingly strict standards, industrialists where impact of smoke released by chimneys on the surrounding area, are required to study the impact of chronic or accidental pollution caused by smoke released from the chimneys and assess the potential dangers to human health and the environment. The heat and mass transfer including smoke in a jet flow from a chimney is remarkably related to turbulent dispersion, one of the interests of turbulence researchers. In order to investigate the mechanism of the turbulent smoke diffusion, laboratory experiments using a wind tunnel is preferable. It is necessary for its wind tunnel testing to realize the smoke dispersion which is similar to that in an actual atmospheric boundary layer.

Many research [1-12] on smoke dispersion from a chimney have been conducted using a wind tunnel. The extensive results of these wind tunnel experiment have been presented and compared with theory, field measurement and numerical simulation results. Several theoretical research have been carried out on smoke dispersion. However, most of them lacked experimental data comparison [2-4]. Said et al. [9] used particle image velocimetry, PIV, to investigate the coherent structures in the near-wake region of a turbulent round-jet ejected perpendicularly from a chimney into a cross flow. Huang and Hsieh [10] classified the jet structure based on the momentum ratio between the cross wind and the jet velocity. Majeski et al. [11] proposed a phenomenological model for predicting the size of a low-momentum jet diffusion flame diluted with an inert gas in a cross flow. Huber and Snyder [12] reported concentration measurements for an elevated point source placed in the lee of a two-dimensional Gaussian model ridge, the height of which was about one-third of the boundary layer thickness. Their results demonstrated the occurrence of significant ground level concentration upwind of the stack source when it was placed at the ridge base within the lower part of the cavity region.
However, it is difficult to reproduce an atmospheric turbulence phenomenon, such as smoke dispersion, in an ordinary-size wind tunnel using high-drag strakes, roughness blocks, a turbulence grid, etc. The wind tunnel experiments of a buoyancy jet with the smoke vertically ejected into the cross flow, which has large-scale turbulent eddies, are essential for the investigation and the precise estimation of smoke dispersion. Our final goal is to construct a turbulent diffusion model for the environmental assessment and prediction of atmospheric dispersion from a point source such as a chimney. In this study, the smoke of heated and unheated jets was observed in the cross flow with the large-scale and grid turbulence, the smoke diffusion width as well as the center of smoke flow was evaluated by processing the instantaneous images taken by the high-speed camera.

2. Apparatus and method
An atmospheric wind tunnel, shown in Fig.1, was employed in the present study and it had a test section of 0.7x0.7 m² in cross section and 6 m in length. A Makita-type active turbulence generator [13], shown in Fig. 2(a), was installed upstream of the test section. The turbulence generator could generate large-
Figure 3. Method for evaluating smoke concentration distribution.

Figure 4. Dispersion structures and normalized smoke-concentration distributions.

scale turbulence with a high turbulence Reynolds number of $R_{\lambda} \sim 390$ at mean cross-wind velocity of $U_\theta = 5$ m/s [13]. That is, a large integral scale, large turbulence fluctuations, and a wide inertial subrange in the energy spectra of velocity fluctuations were achieved. A conventional rectangular grid, shown in Fig. 2(b), was positioned in place of the active turbulence generator, to generate grid turbulence.

The chimney model of $d_i = 4$ mm in inside diameter, $d_o = 19$ mm in outside diameter and $h = 200$ mm in height was placed on the floor of the wind tunnel test section. The smoke generation system for
jecting heated or unheated air with the smoke from the chimney was composed of an air compressor, an air dryer, an air regulator, a flow meter, a smoke generator which was to smoke by using Ondina oil, a surge tank, a heater for generating the buoyancy jet and the chimney as shown in Fig. 1. The origin of a coordinate system was the center of the chimney on the floor in the wind tunnel test section. The cross wind direction was \( x \), the vertical direction which is the direction of the jet velocity at the chimney exit was \( y \), and the span-wise direction was \( z \). The cross-sectional average velocity of the jet at the chimney exit was controlled by the air regulator. The patterns of the smoke dispersion were visualized using a high-speed camera (Photron, FASTCAM SA3 model, 1000 frames/s) and a halogen light.

The present experiments were carried out in the experimental conditions of temperature differences between the cross wind and the jet from the chimney. \( \Delta \theta \), were 0 K, 100 K, 200 K, the jet velocity at the center of the chimney exit, \( U_j \), was from 0.5 m/s to 1.4 m/s, the mean velocity of the cross wind, \( U_0 \), was from 0.3 m/s to 1.0 m/s. That is, the velocity ratio between the jet velocity and the cross wind velocity, \( r \), ranged from 0.5 to 4.7, the momentum ratio, \( R \), ranged from 0.145 to 21.8, and the density ratios between the heated jet and the cross wind, \( S \), were 0.59, 0.74, and 1.00. The mean velocity of the cross flow at the entrance of the test section was measured using a hot-wire anemometer. The vertical mean-velocity profile of the cross flow was uniform around the chimney exit in the large-scale turbulence case. Turbulence intensity, \( u_{rms}/U_0 \), ranged from 9.5% to 11.0% and from 2.9% to 3.5% in the large-scale and grid turbulence cases, respectively.

The smoke concentration distribution was evaluated from smoke visualization images taken by the high-speed camera. By superposing 500 instantaneous images, shown in Fig.3, the time averaged brightness intensity distribution was obtained. Assuming that the averaged brightness intensity, \( C \), of each pixel, was proportional to the smoke concentration, the normalized distribution of smoke concentration, \( (C-C_{\text{min}})/(C_{\text{max}}-C_{\text{min}}) \), was evaluated, where \( C_{\text{max}} \) and \( C_{\text{min}} \) were maximum and minimum pixel values of the average brightness intensity distribution, respectively.

3. Results and discussion
A detailed observation of the behaviors of the heated and unheated jets from the chimney in the cross flow was conducted. The representative images of smoke dispersion mode are shown in Fig.4. The smoke dispersion could be classified into six different patterns, Modes I-VI [14]. These smoke patterns in the downstream field were dependent on the buoyancy force, turbulent motion, inertia force, etc.

The Mode V structure is affected of the meandering motion by the large integral scale in the large-scale turbulence. The smoke structure of the Mode V is dispersed more widely by the meandering motion which cannot be realized in a usual-size wind tunnel with roughness blocks, a conventional turbulence grid, etc. This fact can be noticed that the turbulent eddies corresponding to the integral scale effectively contribute to the meandering smoke diffusion. The Mode VI structure in the large-scale turbulence is a downwash with the hairpin vortices due to the wake of the chimney. Thus, the smoke does not rise above the chimney exit. This is the serious situation for an actual chimney.

In contrast, in the grid turbulence case, Mode I and II can be observed when the buoyancy effect is dominant. The structures of Modes I and II are composed of two longitudinal vortex tubes whose one end connected to the chimney exit. For Mode I, the two vortex tubes are apart from each other. For Mode II, these two vortex tubes are strongly interacted due to the strong buoyancy and its cross-sectional view looks like the inverse shape of a heart-type. Mode III structure comprise of connecting hairpin-type vortices generated by the Kelvin-Helmholtz instability near the jet exit where the velocity shear is high. Mode IV structure is composed of the developed coherent and turbulent vortices by the turbulent motion.

The smoke concentration distribution from the chimney in the large-scale turbulence and the grid turbulence was examined. The normalized distributions of the time-averaged smoke concentration are shown in Fig.4. Figure 4(a) shows the case where Mode II is observed under grid turbulence. Figure 4(b) shows the case where Mode V is observed under large-scale turbulence. The distributions were obtained based on the motion pictures of smoke taken by the high-speed camera. The peak of the normalized smoke concentration distribution in the large-scale turbulence case is lower than that in the
grid turbulence case. The width of the peak in the case of large-scale turbulence is wider than that in the case of grid turbulence. In the case of the large-scale turbulence, the smoke is diffused more widely by the meandering motion of the cross flow, and the concentration peak disappear more rapidly than in the case of the grid turbulence. This can be explained by the significant fluctuations of the velocity and direction of the cross wind. That is, the large-scale turbulence is irregular, unsteady, and chaotic.

As can be seen from Fig.4, the vertical distribution of the time-averaged smoke concentration can be approximated by Gaussian distributions. By fitting a Gaussian distribution to the vertical distribution data of smoke concentration, the diffusion width was obtained as the standard deviation value of the Gaussian distribution, and the center of smoke flow was determined at the peak of the Gaussian distribution. The trajectories of the smoke flow center are shown in Fig.5 for various temperature differences. Fig.5(a) shows the case of grid turbulence and Fig.5(b) shows the case of large-scale turbulence. The jet velocity and cross wind velocity are the same in these charts. Although the smoke of the unheated jet flow down straight, the smoke of heated jet rise with an increase of the downstream distance in the grid turbulence case. In contrast of this, in the large-scale turbulence case, the smoke of the heated jet does not rise so much, and the smoke of unheated jet descend with an increase of downstream distance.

**Figure 5.** The trajectories of the smoke flow center.

**Figure 6.** Variation of the diffusion width of smoke with an increase of the downstream distance.
The variations of smoke diffusion width with an increase of downstream distance are shown in Fig. 6 for various temperature differences. Fig. 6(a) is the grid turbulence case and Fig. 6(b) is the large-scale turbulence case. The conditions of cross wind velocity and jet velocity are the same in these charts. The diffusion width in the large-scale turbulence case is higher than that in the grid turbulence case. That is, the diffusion rate of smoke should be higher under the large-scale turbulence. The diffusion width is not affected so much by the temperature difference in the grid turbulence case, and the diffusion width increases gradually with an increase of downstream distance. On the other hand, the diffusion width increases more rapidly with an increase of downstream distance in the large-scale turbulence case. The diffusion width is large when the temperature difference is large.

The experimental data of dispersion width variations with downstream distance were compared with previous correlations of Sutton [15]

$$\sigma_y = \frac{c_y}{\sqrt{2}} x^{(1-n)/2}$$

(1)

and Passqill & Grifford [16]

$$\sigma_y = \gamma_y x^{a_y}$$

(2)

The results are shown in Fig. 6 by bold solid lines. Constants, $C_y = 0.07$, $n = 0.25$, $\gamma_y = 0.1046$, and $a_y = 0.826$, for neutral air stability were employed to evaluate the diffusion width from these correlations. The width variation estimated from the Sutton’s correlation is close to the experimental results in the large-scale turbulence case, although the width estimated from the Passqill & Grifford’s correlation is larger than the experimental results. This fact suggests that the smoke diffusion from the chimney in the cross flow under the large-scale turbulence is almost similar to the air pollution diffusion from a point source in the actual atmospheric boundary layer of neutral air stability case.

The present experiment was successful in the realization of the smoke dispersion from the chimney which can be observed in the actual atmospheric boundary layer using the atmospheric wind tunnel with the active turbulence grid. The present experimental results can serve as a reference for construction of turbulence diffusion models for the environmental assessment and prediction of atmospheric dispersion from the point source such as chimneys.

4. Conclusions

Flow visualization experiments were performed using a high-speed camera on the diffusing heated and unheated jets with smoke from a chimney in the cross flow with the large-scale turbulence and that with the grid generated turbulence. By analyzing the brightness value of instantaneous images, the time averaged smoke concentration was obtained. The smoke diffusion width and smoke flow center were evaluated from the concentration distribution. The following conclusions were deduced:

(1) The diffusion width of smoke concentration in the large-scale turbulence was higher than that in the grid turbulence. In the large-scale turbulence, the diffusion width increased rapidly with an increase of downstream distance, although the diffusion width increased gradually in the grid turbulence.

(2) In the large-scale turbulence case, the variations of the smoke diffusion width with an increase of downstream distance almost agreed with Sutton’s correlation for neutral air stability case.

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