Wind tunnel measurement of flow and dispersion of power plant emission on the coastal region with complex terrain

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ABSTRACT

The paper is to study in wind tunnel on the flow and plume dispersion in the coastal region with complex terrain. Tufts visualization results show that the wind field of mean flow direction which revealed how the winds were flowing over the hilly terrain model for various wind directions. The reversed flows are observed at the region of the leeside of main hills or mountains of the terrain model. The plume averaged height increases with increasing the topography change parameter of the complex terrain. As the topography of terrain changes from flat terrain type to complex terrain type, the plume vertical dispersion parameter becomes greater.

1. INTRODUCTION

Keelung is a harbor city with about four hundred thousands population. It is also the second largest commercial harbor in Taiwan. The harbor city is located in the mountainous region of northeastern coast of Taiwan. The coastal region is of the complex terrain with varying elevations form 1 m in the harbor city center region to near by mountainous region of 200 m. Refer to Fig.1, Sen-Au fossil power plant was located not far (4 km) from the Keelung city. Fig.2 shows the topographical contours of the coastal region with complex terrain around the power plant. In the case of accidental release of the pollutant emission from the power plant (two stacks 30 m apart), it will give rise of severe air pollution problems and make great impacts on the harbor city air environment. Therefore, it is necessary to offer air pollutant flow and dispersion information for assessing the air pollution impact on the city near-by.

In the past decades, many numerical and experimental studies on the gas diffusion and dispersion have been studied. Typical numerical study on the gas dispersion in the coastal region, like Jin & Raman (1996), they made numerical study on the air pollutant dispersion from an elevated accidental release in the coastal region. The air pollutant numerical simulation of dispersion mostly focused on

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the open country and flat terrain. Wind tunnel experimental studies such as: Kato and Hanafusa (1996) conducted wind tunnel simulation of atmospheric turbulent flow over a flat terrain. Literature on wind tunnel experiments for the air pollutant dispersion over the coastal region with complex terrain like Duijm (1996). He proposed an analysis technique to investigate the wind tunnel modeling dispersion of air pollutants over complex terrain in the Hong Kong Territory. He did not probe thoroughly the terrain effect on the dispersion characteristics. MacDonald et al. (1997) did field experiments of dispersion through regular arrays of cubic structures. They tried to identify the effects of arrays of cubic obstacles on plume dispersion. MacDonald et al. (1998) succeeded to perform wind tunnel modeling of dispersion in arrays of obstacles, and they compared the wind tunnel results with the measurements of full-scale field trials.

In order to offer the assessment of pollution dispersion for coastal region with complex terrain, physical modeling of the pollution dispersion was carried out in this study. We mainly investigate the variation of flow and dispersion parameter in such coastal region with complex terrain.

![Figure 1: Location of Sen-Au power plant.](image)

![Figure 2: Topographical contours around the power plant region.](image)

2. **EXPERIMENTAL WORKS**

Experiments were conducted in the environmental wind tunnel. The test section of the wind tunnel had the cross section of 2m by 1.4m and 12.6m long. Four spires were placed at the entrance of the test section and roughness elements succeeded to be arranged 9 m long. This arrangement created a fully developed turbulent boundary layer flow, which was used as the approaching flow. The Reynolds number of the simulated approaching flow is about $\sim10^5$. This is sufficient for the turbulent flow similarity requirement of the critical number of $\sim10^4$ (Snyder (1981)).
An X-type hot-wire incorporating with the TSI IFA-300 constant temperature anemometer was applied to measure the turbulent flow signals. Topographical model was constructed at a scale of 1 to 2000. The model was 2 m long and 2 m wide. It was made layer by layer through a number of vertically mounted polystyrene plates of 1 cm thickness around the isopleth of height. The roughness length in the model keeps about 2 mm. As suggested by Snyder (1981), it assures flow to avoid laminar sublayer occurring in the model for flow simulation.

Exact simulation of stack discharge effluent requires rigorous similarities between the prototype and model. It is difficult to meet the rigorous requirements, but consideration of relaxed similarities for the momentum length scale, $l_m$, between the prototype and model are sufficient for present study of approximated simulation (Snyder (1981)). The heights of power plant two stacks are 75 m with inner diameter of 5.2 m and 4.27 m, respectively. The prototype discharging velocity of two stacks are 20.16 m/s and 19.7 m/s. The densimetric Froude number of two stacks discharge effluent are about 41.4 and 14.5. And momentum length scales for two stacks are 5.25 m and 4.21 m of full scale. For the model experiments, we choose the free stream velocity of 2.56 m/s. And the momentum length scales of two model stacks are 0.0021 m and 0.0017 m.

For flow direction visualization of the wind over complex terrain in coastal region, tufts were used as indicators of flow direction. The tufts are mounted on the model surface at a height of 7 cm, which corresponds to 140 m full scale. Visualization of the flow direction was conducted by employing the charged couple detector (CCD). The top view image of wind over the complex terrain model was grabbed at a sampling rate of 10 frames per second. We took an average of sampled frames of images for each run of flow direction visualization with a period of 30 seconds.

Methane was used as tracer gas, and it mixed with the standard gas. The mixed gas emitted from two stacks as the discharge of sources in the experiments. The rake of sampling tubes was placed at the sampled position. The tube-rake is composed of ten tubes. A cam mechanism is employed for design of the pump to suck the tracer sample to the airbags through the ten tubes simultaneously and efficiently. Each sample was taken for 5 minutes. The sampled tracer gas in airbag was analyzed with FID (Flame Ionization Detector) to count the methane concentration.

3. RESULTS

The flow and dispersion of pollution plume in the complex terrain of coastal region were measured and analyzed. The effect of topography change of the complex terrain on plume dispersion characteristics, such as the plume average height, vertical concentration profiles, and vertical dispersion parameter were discussed. The northeasterly wind is the prevailing wind direction from statistical analysis of the long period of wind record (1969-1999) of Keelung city meteorological station. And the northwestern and western regions of the model are areas near the city center. Therefore, we conducted experiments of flow direction visualization with tufts for such three wind direction cases, that is northeasterly, southeasterly, and easterly winds over the complex terrain of model.

3.1 Approaching flow

The neutral atmospheric turbulent boundary layer flow was simulated as the approaching flow over the region around the stack source, which can be classified as suburban area terrain type. The mean velocity profile of the simulated turbulent boundary layer flow is shown in Fig.3. The mean velocity profile is approximated by the power law equation. The present simulated turbulent boundary layer flow is with a power exponent, $n$ is 0.222. Counihan (1975) indicated the power index range 0.21-0.23 for suburban area. The present simulation of approaching flow fit to the power index range for terrain type of suburban area as indication of Counihan (1975).

The simulated turbulence intensity profile is shown in Fig.4. It is seen that the simulated longitudinal turbulence intensity increases with decreasing the height. As the height close to the
ground, the longitudinal turbulence intensity exceeds 20%. Although Counihan (1975) only summarized that the longitudinal turbulence intensity for heights 2~30 m above ground level for rural area fell in the range of 0.1 to 0.2. It is reasonable to estimate that the longitudinal turbulence intensity at the height close to the ground in the terrain type of suburban area is larger than 20%.

Fig. 5 shows the comparison of the present simulated longitudinal turbulent velocity spectrum at $Z/Z_{ref}=0.76$ with as appeared the Karman power spectrum equation. Maeda and Makino (1988) rewrote the Karman power spectrum equation and it was expressed as following form:

$$S_u(n) = \frac{2u' L_{xu}^u}{U[1 + \left(\frac{2cnL_{xu}^u}{U}\right)^2]^2}$$

In the figure 5, the spectrum density, $S_u(n)$ and frequency, $n$ are normalized, and they are denoted by $US_u(n)/u'L_{xu}^u$ and $nL_{xu}^u/\bar{U}$, respectively. Here $u'$ denotes the mean square of longitudinal velocity fluctuation, $\bar{U}$; $c$ is coefficient of 4.2065; $L_{xu}^u$ is the integral length scale of longitudinal velocity in x direction; $\bar{U}$ is the longitudinal mean velocity at the height of $z$. The integral length scale is obtained by multiplying the integral time scale, $T_E$ with the longitudinal mean velocity, $\bar{U}$. The integral time scale, $T_E$ is computed by integrating the longitudinal velocity autocorrelation coefficient function, $R_u(\tau)$. It is found that a satisfactory agreement is achieved for the turbulent approaching flow structure simulation.

![Figure 3: Mean velocity profile of approaching flow.](image-url)

![Figure 4: Turbulence intensity profile of approaching flow.](image-url)
3.2 Flow direction visualization of wind over complex terrain

Fig. 6 shows the tuft observation for flow direction of easterly wind over the coastal complex terrain at height of $z/H = 1.87$, where $H$ is the stack height. In the figure the arrows point in the direction of the tufts. The wind flow direction can be observed from the arrows. Fig. 7 is the tuft observation for flow direction of northeasterly wind over the coastal complex terrain at height of $z/H = 1.87$. Fig. 8 shows the tuft observation for flow direction of southeasterly wind over the coastal complex terrain at height of $z/H = 1.87$. 

Figure 6: Flow visualization of tufts for easterly wind over the coastal region with complex terrain.

Figure 7: Flow visualization of tufts for northeasterly wind over the coastal region with complex terrain.
In summary, topographical profiles in some regions are more irregular, therefore the winds accordingly are flowing irregularly. Reversed flow regions are seen at the tuft indicators observations. In general such regions are the leeside of mountains or hills. We find that the flow turbulence is largely increased when the wind over the mountains. This is shown by the unsteadiness of tufts. The flow turbulence differs from place to place and with the highest turbulence occurs on the leeside of the hills or mountains as expected. The reversed flow is viewed at some regions which are generally the leeside of main hills or mountains.

3.3 Flow and turbulence characteristics of wind over complex terrain

The mean wind velocity and longitudinal turbulence intensity profiles for different downwind stations of sources for easterly wind over the complex terrain are shown in Fig. 9. Results indicate that mean wind speed increased (i.e. speed-up phenomenon) at the hill or mountain crest. The turbulence intensity increases as measured locations shift to leeside of hills or mountains. Fig. 10 is the mean wind velocity and longitudinal turbulence intensity profiles for different downwind stations of sources for northeasterly wind over the coastal complex terrain. For southeasterly wind over the coastal complex terrain, the mean velocity profiles and longitudinal turbulence intensity profiles at different downwind stations of sources are shown as Fig. 11.

In summary, the speed-up phenomenon occurred when the wind flow over the topography with hill or mountain crests. And the turbulence intensity increases as the topography strongly change.
3.4 Concentration distribution analysis

The tracer concentration $C$ is scaled by the stack height $H$, emission discharge $Q$, and ambient cross wind speed $U$ as the dimensionless concentration $K=CH^2Q/U$.

For easterly wind over the coastal complex terrain, the horizontal and vertical dimensionless concentration contours are shown in Fig.12. It is noted that due to hills existed beside the sources, the double high horizontal concentration contours occurred at the near-by region of power plant two stacks sources.

The horizontal mean concentration profiles for different downwind distances of source for easterly, northeasterly and southeasterly winds over the complex terrain are shown in Fig. 13. The vertical mean concentration profiles along the downwind distance of source for easterly wind are shown in Fig. 14. The broken line shown in the Fig. 14 is the topography of hilly terrain, and solid lines are the concentration profiles predicted by reflected-Gaussian theoretical formula for flat terrain. Fig. 15 shows the vertical mean concentration profiles along the downwind distance of source for northeasterly wind. And Fig. 16 shows the vertical mean concentration profiles along the downwind distance of source for southeasterly wind. As comparing the results of Fig. 14, 15, and 16, it is found that the plume vertical mean concentration profiles downwind of source for hilly terrain apparently deviate from the formula predictions of reflected-Gaussian theoretical formula for flat terrain.
3.5 Topographical effect on the vertical dispersion parameter of plume

To characterize the elevation variation of hilly terrain, the topography change parameter is proposed. The cumulative root mean square of elevation fluctuation for topography along the downwind distance is designated as, $s(z_{rms})$. Here $z_{rms}$ is the root mean square of topography elevation.
fluctuation. The slope of $s(z_{rms})$ is defined as the topography change parameter, i.e. $d[s(z_{rms})]/dx$. It is obviously that the topography change parameter for flat terrain is zero. The topography change parameter is applied to analyze the effect of topography of hilly terrain on the plume vertical dispersion. Fig. 17 plots the cumulative root mean square of elevation fluctuation for topography as functions of downwind distances for wind over various complex terrains. The slope of the line shown in Fig. 17 is the topography change parameter. Results indicate that the averaged topography change parameter for easterly wind case is the largest among the three cases. And the averaged topography change parameter for southeasterly wind case is the smallest.

Figure 15: Vertical mean concentration profiles along the downwind distance of source for northeasterly wind over the hilly terrain

Figure 16: Vertical mean concentration profiles along the downwind distance of source for southeasterly wind over the hilly terrain

Figure 17: Topography change parameter along the downwind distance of source for wind over various complex terrains.
Plume vertical dispersion parameter $\sigma_z$ is adopted to characterize the extent of spread for plume in vertical directions. It is estimated from the measured concentration distributions and here is defined as:

$$\sigma_z = \left[ \frac{\int_{-\infty}^{\infty} z^2 Cdz}{\int_{-\infty}^{\infty} Cdz} \right]^{\frac{1}{2}} - z_c^2$$

(2)

where $C$ is the measured concentration; $z$ is the vertical ordinates of Cartesian coordinates. And $z_c$ defined as the plume average height, is calculated by,

$$z_c = \left[ \frac{\int_{-\infty}^{\infty} z Cdz}{\int_{-\infty}^{\infty} Cdz} \right]$$

(3)

Fig. 18 shows the variations of vertical dispersion parameters variations downwind of sources for various winds over the coastal complex terrains. The vertical dispersion parameter of plume in flat terrain for neutral condition, i.e. Pasquill stability category D, (Pasquill (1976)) is calculated in accordance with the equation proposed by Martin (1976).

$$\sigma_z = ax^b + f$$

(4)

where $\sigma_z$ is in meters, and $x$ is the downwind distance, and it is expressed in kilometers. When $x \leq 1$ km, $a=33.2$, $b=0.725$, $f=-1.7$; and $x \geq 1$ km $a=44.5$, $b=0.516$, $f=-13.0$.

Fig. 18 reveals that the vertical dispersion parameters of present three complex terrain cases are larger than that of for flat terrain measured or predicted of flat terrain by formula of Martin (1976). This implies that as the topography change from flat terrain to complex terrain, it will cause the increase of the value of vertical dispersion parameter. Also it is seen that vertical dispersion parameter increases as the downwind distance of the source increases for wind over different complex terrains.

Fig. 19 shows the plume averaged height, $z_c$ as function of downwind distances of source for wind over various complex terrains. As revealed from Fig. 17, the averaged topography change parameter for southeasterly wind case is the smallest among three cases. So the plume averaged height along the downwind distance of source is the smallest among three cases.
4. CONCLUSION

Flow and dispersion of pollution in the hilly terrain was studied experimentally in the wind tunnel. Tufts visualization technique was employed to observe the wind field of mean flow direction. Methane tracer concentrations were measured to analyze the pollution plume dispersion characteristics.

Tufts visualization results show that the wind field of mean flow direction which revealed how the winds were flowing over the hilly terrain model for various wind directions. The reversed flows are observed at the region of the leeside of main hills or mountains of the terrain model. The plume averaged height increases with increasing the topography change parameter of the complex terrain. As the topography of the terrain changes from flat terrain type into complex terrain type, the plume vertical dispersion parameter becomes greater.

REFERENCES