Chapter 4 Weather Conditions, and the Variation and Distribution of the Concentration of Air Pollutants

4.1 Effect of Weather Conditions

4.1.1 Preface

The meteorological factors that most affect the generation and sustenance of the air pollution are the wind and thermal stability of the atmosphere. Thermal stability of the atmosphere is closely related with a vertical variation of the atmospheric temperature. It is very important to have a correct understanding of the structure of lower layers of the atmosphere, since the air pollution occurs at the bottom layer of atmosphere from the ground to the altitude of several kilometers.

4.1.2 Atmospheric Boundary Layer

Because many of the air pollutants are released adjacent to the ground, their behavior in the environmental air is strongly affected by the weather in lower layers of the atmosphere. The Earth absorbs energy from the Sun at the ground surface. Various weather conditions are caused by the release of this energy in the atmosphere. The atmospheric layer that directly receives the effect from the ground surface is, that is, the atmospheric boundary layer. Although the thickness of this layer is dependent on the characteristics of the ground surface and weather conditions, it generally ranges from 1 to 3 km. The atmosphere above this layer is called the free atmosphere. Within the atmospheric boundary layer, the layer from ground surface to a few tens of meters above surface is called the surface boundary layer.

4.1.3 Vertical Variation of Air Temperature

The degree of atmospheric diffusion is greatly affected by the vertical variation of air temperature. In the standard atmosphere, the air temperature decreases by 0.65℃ as the altitude increases by 100 m. However, this value changes considerably as the weather condition changes. The situation of temperature variation that affects the diffusion of air pollutants most is the temperature inversion layer. This is a condition where the temperature of the lower layer is below that of the upper layer. As the air pollutants are trapped in the temperature inversion layer and would not diffuse, the concentration of air pollutants is increased. The radiation inversion and the subsidence inversion are known as two major causes of the temperature inversion. Particularly, the radiation inversion which often appears in a clear night of winter season is the major factor for the generation and sustenance of a high concentration of air pollution. On the other hand, in the daytime of a fine weather, the ground is heated by sunlight to generate a thermal convection, and the vertical mixing of air is enhanced. This atmospheric layer is called the mixed layer. The height of mixed layer during daytime is proportional to the square root of the accumulated solar radiation, I (cal/m^2). From the observational result in Tokyo during summer, the height of mixed layer $Z(t)$ (m) up to 12 o'clock is known to be approximately expressed by Eq. (1). After 12 o'clock, the height is proposed to be derived by multiplying a certain factor to this value.' Specifically, factors such as 1.127 at 15 o'clock, 0.696 at 18 o'clock, and 0.357 at 21 o'clock are proposed. As those values strongly reflect the regional characteristics, those must be checked with the actual observation at each site.

$$Z(t) = 76.8\, \mathrm{I}^{\,0.499} \quad \cdots\cdots \quad (1)$$

Japan is usually covered with a high pressure air mass centered in the north Pacific during summer, and a fine weather is sustained. Accordingly, there often appears a subsidence inversion layer. As the mixed layer grown during daytime is suppressed by this inversion layer, a high concentration of photochemical smog will be generated in the atmospheric layer from the ground to about 1,000-2,000 m upward.

4.1.4 Vertical Distribution of Temperature and Diffusion

From observations of the behavior of smoke exhausted from chimneys, the relationship between the smoke flow and the vertical distribution of temperature has been investigated. When a dry air mass adiabatically ascends for 100 m in the atmosphere, its temperature would drops by 0.98℃. When the atmospheric condition shows the same value as this temperature drop, this atmosphere is said to be thermally neutral. When the temperature drop rate is larger than this value, the atmosphere is called thermally unstable, whereas when it is smaller, the atmosphere is called thermally stable. Also, when the temperature of the upper layer is higher than that of the lower layer, the layer is said to be in the temperature inversion state, as described in Section 4.1.3.

The behavior of smoke is categorized into several representative types in accordance with the vertical distribution of temperature. When the atmosphere is in a neutral or a rather stable state, the smoke will diffuse in the form of coning type. Such a condition would occur in the cloudy daytime weather or in relatively strong windy weather. In the stable layer or inversion layer often seen in winter nights, the smoke will diffuse in the form of fanning type as the vertical diffusion is suppressed. In a fine weather with low wind as often seen in summer daytime, the lower layer of atmosphere becomes unstable, while the upper layer will be stable. In this case, the smoke would meander to show a loping type of behavior. When there exists a subsidence inversion layer in the upper atmosphere, the smoke will diffuse in the form of trapping type of behavior as its upward diffusion will be suppressed. If there are any unstable state simultaneously in the lower layer, the smoke will diffuse rapidly toward the ground, and brought about a high concentration will be near the ground. Such a condition is called the fumigation.

When the bump of ground, or the surface roughness varies, an internal boundary layer will be formed. For instance, when the wind blows from the sea or lake, which has a small surface roughness, to the land with a large roughness, an internal boundary layer with larger atmospheric disturbances than on the sea or lake will be developed on the land side. When the air pollutants, generated in the factories and power stations in coastal areas, would reach to the internal boundary layer of landside with larger disturbances from the sea side areas where the disturbance is smaller, there might occur a rapid mixing and diffusion and bring about a high concentration of pollutants near the ground. This phenomenon is called the internal boundary layer fumigation.

4.1.5 Vertical Distribution of Wind

The vertical distribution of wind is also an important weather factor. The wind distribution between the ground to a height of about 100-200 m is empirically represented by Eq. (2) ;

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p \qquad \cdots\cdots \qquad (2)$$

where u_1 is the wind velocity at a height of z_1. The meaning of exponent p will be explained as follows. The of wind velocity increases exponentially as the altitude increases, and the amount of increase varies depending on the physical characteristics of the ground surface and the degree of stability. The value of exponent p is roughly 0.25 in the neutral state, 0.1-0.2 in the unstable state, and about 0.3 in the stable state. Even in one day, it becomes smaller in the daytime and larger in the night. If the surface roughness varies, the exponent p would increase as the roughness becomes larger. Accordingly, p is larger in the urban areas than in the suburbs. The value of p in the urban area is about 0.2-0.4.

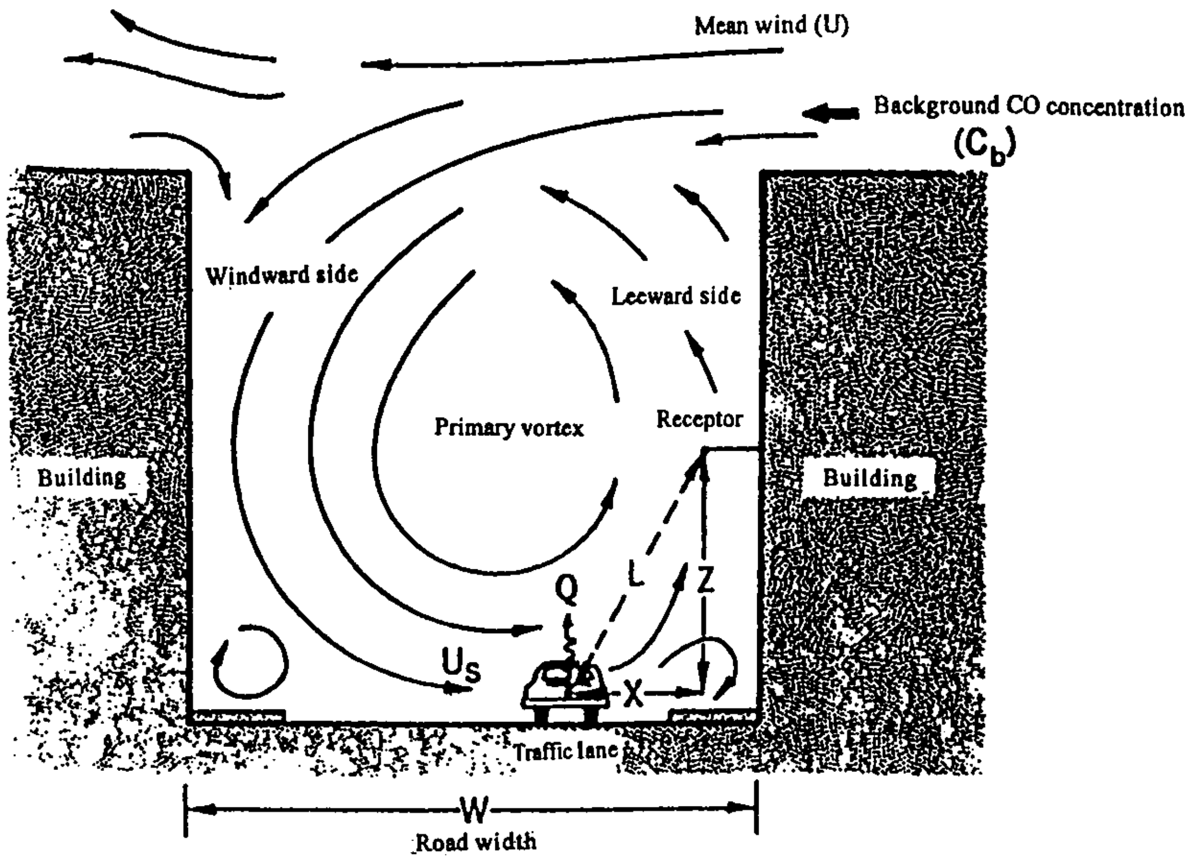
4.1.6 Urban Wind and Air pollution

The situation where roads are surrounded by buildings to form an artificial canyon is called the street canyon. In the street canyon, a special type of wind is generated and it gives a significant effect on the air pollution in the adjacent area. The urban wind is closely related with physical conditions such as the height and density of buildings and the width of roads, and also with weather conditions such as the wind direction and velocity and the thermal stability of the atmosphere. Generally, the most typical situation is brought about when the wind blows perpendicularly to the street. The wind distribution in the street canyon in the above situation is illustrated in Fig.4.1.1.

In this situation, the concentration at a receptor, C_L would be expressed by Eq. (3):

$$C_L = \frac{Q}{k_1 k_2 (U + 0.5)[(x^2 + z^2)^{\frac{1}{2}} + 2]} \qquad \cdots\cdots \qquad (3)$$

where H is the height of building (m), W is the width of street (m), X is the horizontal distance from centerline of the street to the receptor (m), Z is the vertical distance from centerline of the street to the receptor (m), U is the wind velocity above the street canyon and Q is the exhaust source strength (mg/m/s). $k_1 k_2$ is a constant, and is empirically determined as $K = \frac{1}{k_1 k_2} = 7$. Although this equation is quite simple, it is useful to generally understand the maximum concentration found around the street. However, the value of K varies significantly depending on the situation of the streets and the stability, and therefore appropriate studies such as tracer gas experiments and wind tunnel experiments are necessary to validate the result.



Source: (Cited from Johnson, W.B., Ludwig, F.L., Dabberdt, W.F. and Allen, R.J., An Urban Diffusion Simulation Model for Carbon Monoxide, Journal of the Air Pollution Control Association, Volume 23, No. 6, 490-498 (1973))

Fig.4.1.1 Wind Distribution in Street Canyon

4.1.7 Urban Boundary Layer and Air Pollution

The local weather variation caused by the existence of cities, such as an urban boundary layer, has a very close relationship with the distribution of air pollutants. The urban boundary layer is a type of the internal boundary layer. Generally, the urban area has larger roughness than the suburbs because buildings are tightly concentrated. Also, thermal characteristics of the surface and the amount of exhausted heat are different, and therefore the urban boundary layer is formed by mechanical and thermal factors. The urban boundary layer is known to develop from windward outskirts of the city toward the city center. If the distance from outskirts is denoted by X and only the balance of sensible heat is considered, the thickness of urban boundary layer, $Z_h(X)$ at the position X is expressed by Eq.(4). This equation works primarily for the situation in winter nights. In the equation, U is the general wind velocity,

γ is the temperature gradient in the ground surface inversion layer, and $\frac{Q_s}{C_p\rho}$ is the of sensible heat flux.

Furthermore, as Eq. (5) holds when the difference between the temperature of suburbs, Tr and that of the city, Tu is denoted by $\Delta\ Tu-r$, the temperature difference between the point X in the city center and the suburbs is represented by Eq. (6). This is the situation called the heat island.

$$Z_h(X) = \left(\frac{2}{U\gamma}\int_0^x \frac{Q_s}{C_p\rho}\,dx\right)^{\frac{1}{2}} \quad \cdots\cdots \quad (4)$$

$$\Delta Tu-r \propto \gamma\ Z_h(X) \quad \cdots\cdots \quad (5)$$

$$\Delta Tu-r \propto \gamma^{\frac{1}{2}} U^{\frac{1}{2}} \left(\int \frac{Q_s}{C_p\rho}\,dx\right)^{\frac{1}{2}} \quad \cdots\cdots \quad (6)$$

From Eq. (3), it is found that the temperature difference between city and suburbs is proportional to the square root of total sensible heat added through the distance X from the outskirts, and is inversely proportional to the square root of the general wind velocity in the city. This heat island, where the temperature is higher at the city center than at surrounding areas, causes the stagnation, circulation and sustained and elevated concentration of air pollutants. The air pollutants released in the interior of the city are trapped within this urban boundary layer to cause highly concentrated air pollution. On the other hand, when the pollutants released from facilities located in the windward side are taken into the region of $Z_h(X)$ in urban area through the urban boundary layer surfaces by being transferred through atmosphere without much diffusion or dilution in the stable layer above, an internal boundary layer fumigation occurs.

4.1.8 Synoptic Meteorology and Local Meteorology

The velocity and direction of wind and the stability of atmosphere are basically controlled by meteorological phenomena of synoptic scale caused by the air flow of global scale and the physical characteristics of ground surface, but the variation of local weather also gives significant effects on the distribution of air pollution.

Among others, the sea-land breeze is particularly important. As the sea and lake have large heat capacity, their diurnal variation of temperature is relatively small, while it is large in the land area. As a result, the temperature on land area becomes higher than that of water surface during the daytime while lower in the night. Thus the temperature difference is caused between airs above the land and the water, which then causes the atmospheric pressure difference. Because of this difference, the air flows from the sea and lake toward the land in the daytime while the direction is reversed in the night. This is the sea-land breeze. The sea-land breeze has a characteristics of the gravity flow, and a conservative wind field is formed at the head of the breeze where a vortex is formed. Thus the air pollutant would be trapped within this field to cause a high concentration. As the sea-land breeze moves with time, the area of high concentration would also move with it. The line of discontinuity of the wind formed, when the sea wind and the land wind comes in, is called the sea breeze front and the land breeze front, respectively. In mountainous areas or basins, the air temperature at the same altitude is different for the slope and the valley, and the wind blows from the valley to the mountain in the daytime, and in the opposite direction in the night. The air circulation caused by this mountain-valley breeze would give effect to the air pollution.