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A Preliminary Report on the Experiment of Thermal Convective Circulation under the Inversion Layer in the Stratified Wind Tunnel

by

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Abstract

The stratified wind tunnel in which the density of air gradually changes with height is available for experimental studies on thermal convective air currents under the developed thermal inversion layer. The convective currents do not thrust through the upper light layer, but spread out horizontally, and the circulation pattern is similar to that of the so-called heat island obtained by numerical simulation. It suggests the mechanism of the local flow patterns of urban heated and urban polluted air.

1. Purpose of the experiment

One of the authors has surveyed the temperature at the ground surface in Tokyo, using several types of airborne infrared radiometers on four August days in 1971 and 1972 (TSUCHIYA, 1972ab). There are many observational data showing that the difference of surface temperature reaches 20°C to 30°C according to various surface conditions. For example, the temperature is higher than 50°C at the surfaces of school grounds and congested areas with wide roads and large buildings, while it is lower than 30°C at surfaces of rivers and green areas on fine summer days.

There are several cases where a spot area with high temperature at the surface happens to be surrounded by greenery-covered areas with lower temperature at the surface. It is supposed that this is due to the vertical and horizontal circulations that exist locally between the high- and the low-temperature area. These local circulations often develop even under the thermal inversion layr above urban surfaces with green area when the general wind is weak.

We intend to make experimental circulations which are similar to the above-mentioned circulations for studying their characteristics.

2. Method of the experiment

We laid a square heat plate on the base of the stratified wind tunnel and constructed two smoke sources at both sides of that plate (See Table 1 and Figure 1).

Table 1. Some characteristics of the stratified wind tunnel.

Observation field	length: 160cm		height: 50cm		width: 50cm
Wind speed range	5-300 cm/sec				
Specific gravity	5	10	15	20	30(height from the base: cm)
distribution by heght	1.16	1.10	1.06	1.03	1.01(specific gravity)

A flow with stable stratification is made by the addition of freon gas (specific gravity ratio to the air is 4.7) into the ordinary air in the wind tunnel. We get a stably stratified flow layer when the ratio (ρ_1/ρ_0) of the lowest air layer density to the air layer near the ceiling in the working section of the stratified wind tunnel is about 1.2, where ρ_1 is the density of air mixed with freon gas and ρ_0 is the air density.

We decreased the speed of air flow in the wind tunnel, and at the same time, we warmed the heat plate up to 60°C. The temperature difference between the heat plate and the base of the wind tunnel becomes 30°C or more. And the pattern of air flow was observed by a paraffin smoke. The vapour of paraffin mixed with freon gas was poured into the wind tunnel through the two smoke holes when thermal convective air currents were considered to occur under the stratified layer.

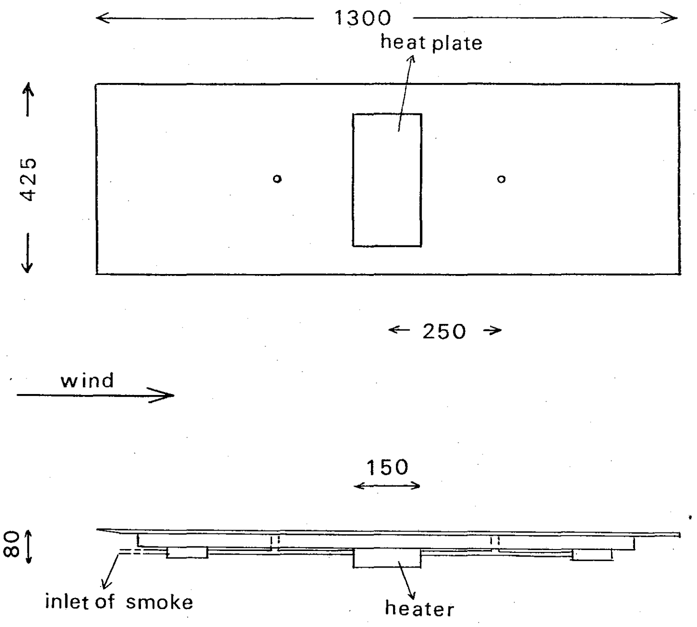

Fig. 1. Experiment units in the stratified wind tunnel (in mm).

3. Thermal convection

Figure 2 shows the paraffin smoke circulation induced by the heat plate through two smoke sources. And Figure 3 illustrates that circulation pattern based on the observation at the same time of Figure 2.

The smoke currents are heavier than the air mixed with freon gas at the lower layer of the wind tunnel, so, after rising at first, they sink near the smoke sources. Affected by the suction effect of the convective circulation induced by the heat plate, the right-hand smoke current sinks to the left and the left-hand smoke current sinks to the right. Fallen smoke currents are swallowed up over the heat plate slowly then gradually fast, and they vertically rise up more fast. The rising of smoke currents ceases half-way up to the ceiling of the wind tunnel, and the concentrated smoke currents become an expanded semicircular shape, and then spread horizontally both sides of the heat plate without much vertical dispersion.

A small part of the smoke particles sink down very slowly on leaving the position of the heat plate. Those smoke currents are swallowed up again into the abovementioned circulation system.

We can regard this circulation system as the same phenomenon that is generated in the atmospheric thermal inversion layer when a heat source exists in its bottom

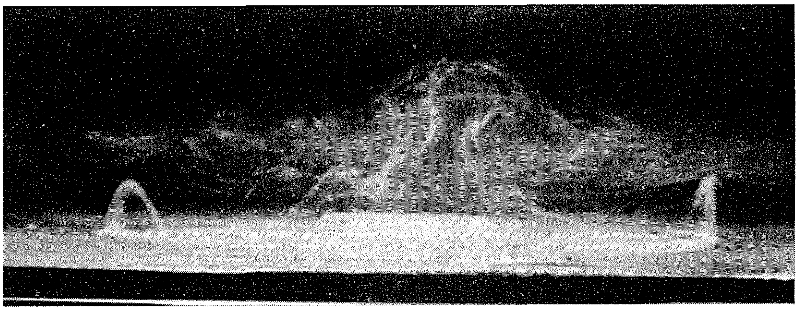

Fig. 2. Thermal convective circulation in the stratified wind tunnel.

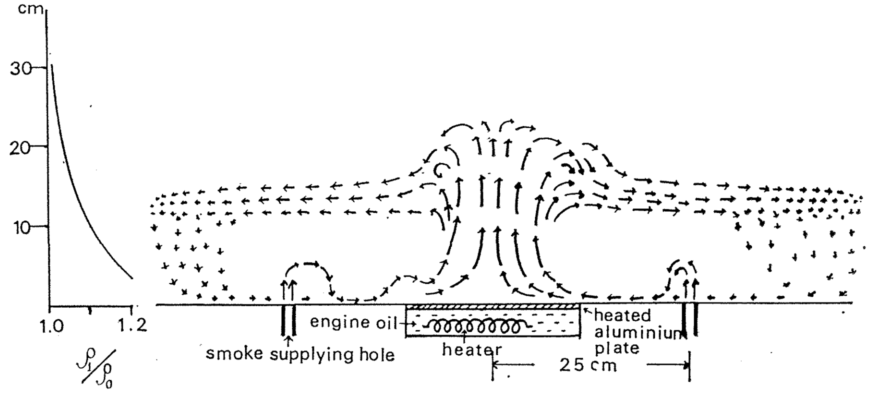

Fig. 3. Schematic flow pattern shown in Fig. 2.

layer although there are some restrictions related to the strengths of inversion and heat supply. There are similar conditions in density profiles of the thermal inversion layer and stratified layer in that wind tunnel; the specific gravity of the upper layer is lighter than that of the lower layer.

In this experiment, the air above the heated plate becomes lighter than the ambient air, and then rises. This rising air current spreads out on each side of the heat plate when its density becomes the same as in the middle layer after becoming heavy by cooling. Some smoke particles sink very slowly to the bottom layer because their density is rather high.

We can say that this experiment shows the vertical structure of local air currents in the developed thermal inversion layer when there is a concentrated heat source which is an ordinary urban surface structure and not an extremely high temperature such as a chimney.

4. Comparison between a wind-tunnel convective circulation and the numerical simulation of an urban heat island circulation

An urban heat island is one of the so-called man-made climates, and the existence of a characteristic heat island circulation was numerically and observationally studied by several researchers recently (Delage and Taylor, 1970; Findlay and Hirt, 1969). Figure 4 is an example of numerical simulation by Delage and Taylor (1970) under an elevated thermal inversion. Our thermal convective circulation in the stratified wind tunnel looks very closely similar to their simulation pattern.

Although our considerations for that experiment and their conditions for their simulation are not the same as regards the many parameters of horizontal and vertical

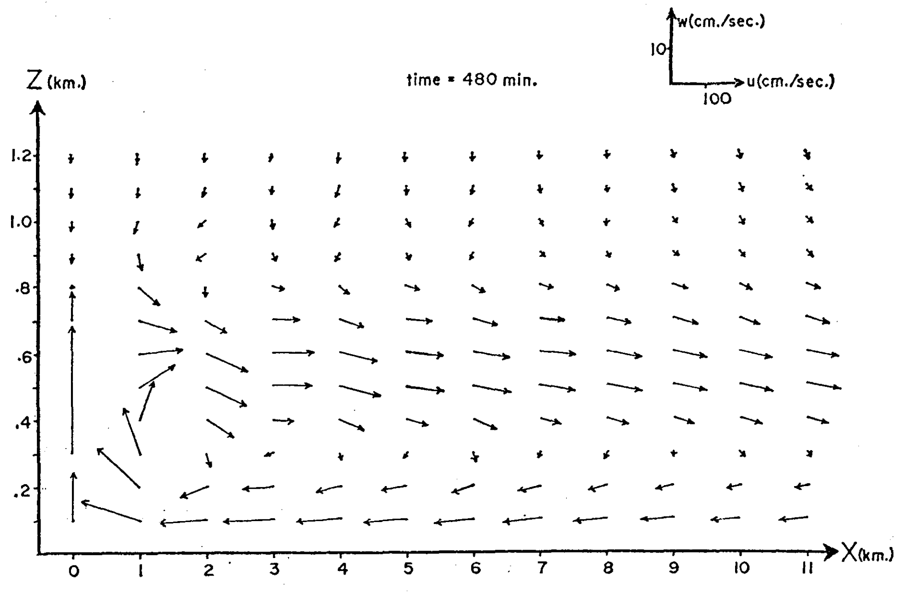

Fig. 4. A simulation example of heat island circulation obtained theoretically (after Delage and Taylor, 1970).

dimensions, heat gradient, stability of thermal inversion, environmental wind speed, etc., but the similarities of both circulation patterns clearly suggest the same generation mechanism.

5. Further remarks on the thermal structure of a large city

There is a considerable increasing trend for man-made heat generated in urban areas. In the urban area of Tokyo, this amounts to 10–15% of the insolation energy in summer, and sometimes more in winter (TSUCHIYA, 1972b). We can regard the role played by man-made heat to be considerable in the recent secular rising trend of air temperature in Tokyo. However, the mechanism of man-made heat and its thermal contribution to the urban air temperature are not clear.

Our wind-tunnel experiment suggests that there are some cases in which the thermal air plume generated over the high temperature area at the surface does not penetrate into the thermal inversion layer and that the plume horizontally disperses along the inversion layer. It is possible to say that such horizontally dispersing thermal plume maintains the higher temperature of the air layer above the urban area when the inversion layer is stable. The polluted air in such a thermal plume lets fall heavier particles and gases through its dispersion process, and a locally dense polluted area occurs near the higher temperature area at the surface. We consider that this is a dense pollution induced by the suction effect of the thermal air plume.

We intend to make a pattern of thermal convective circulation under the condition of thermal inversion. The generation of a two-dimensional circulation of air flow in the thermal inversion layer was successfully achieved in the stratified wind tunnel.

Our experiment is restricted to a simple heat model and the thermal inversion is replaced by the density gradient layer. Modifications of experimental systems and further quantitative considerations of the experimental processes will be called for to solve the problem of heat island circulation.

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成層風洞による逆転層内の熱対流の実験についての序報

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上層を軽く下層を重くした密度成層を構成する成層風洞を用いて，発達した気温逆転層に相当する条件下での熱対流の実験を進めた。熱気流は軽い層を突き抜けることがなく，逆転層内を水平に広がったが，この循環は数値シュミレーションによって示されたいわゆるヒートアイランド循環と同じ形のものである。都市熱や都市汚染空気の局地的な流れの形と機構についての示唆がこれによって得られる。