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Characteristics of spiral vortex flow and its application to control indoor air quality

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CHARACTERISTICS OF SPIRAL VORTEX FLOW AND ITS APPLICATION TO CONTROL INDOOR AIR QUALITY

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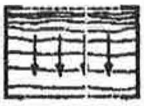
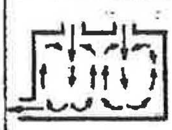
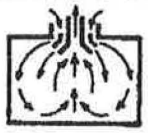
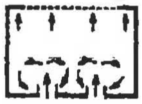
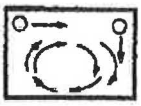
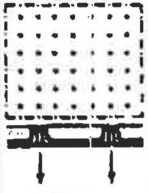
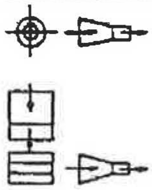
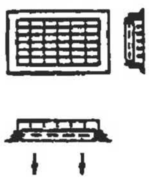
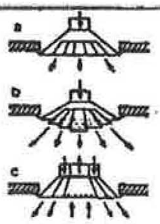
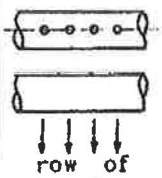
Introduction

While spiral vortex flow has been utilized in various fields of engineering, there have been few examples of its application in the fields of ventilation and air conditioning. The authors have been conducting some experimental studies to clarify the possibilities and limitations of utilizing the spiral vortex flow principle to control indoor air quality. The main focus at present is the measurement of the concentration distribution of air contaminants in a space having a spiral vortex flow and comparison of the measured values with those of conventional ventilation systems.

Spiral Vortex Flow and Transport of Air Contaminants

Table 1 illustrates the types of air distribution for indoor climate control. Of these, the most common types are displacement and mixing airflows in which air contaminants are either displaced or diluted with supply and/or room air.

Table 1. Types of air distribution for indoor climate control.

	displacement flow	mixing flow				spiral vortex
airflow pattern						
air supply examples	 multiple -hole plate	 nozzle	 grill	 anemostat	 under-seat air supply	 row of nozzles

The spiral vortex flow exhibits unique characteristics. This flow is seen in nature in, for example, tornadoes and typhoons. As an idealized model of this flow, a "Rankine vortex" is shown in Fig. 1. A "core" with radius r is generated at the center of the vortex. Outside of the vortex core is a free vortex in which the tangential velocity component becomes slower with increasing distance from the center axis. Inside of the core is a forced vortex in which the tangential velocity component becomes faster with increasing distance. Static pressure decreases toward the center of the core.

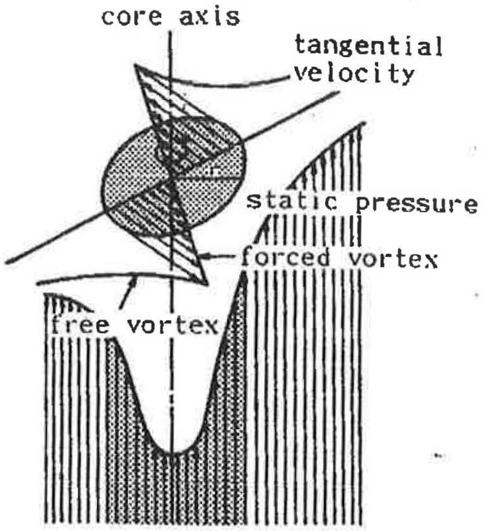
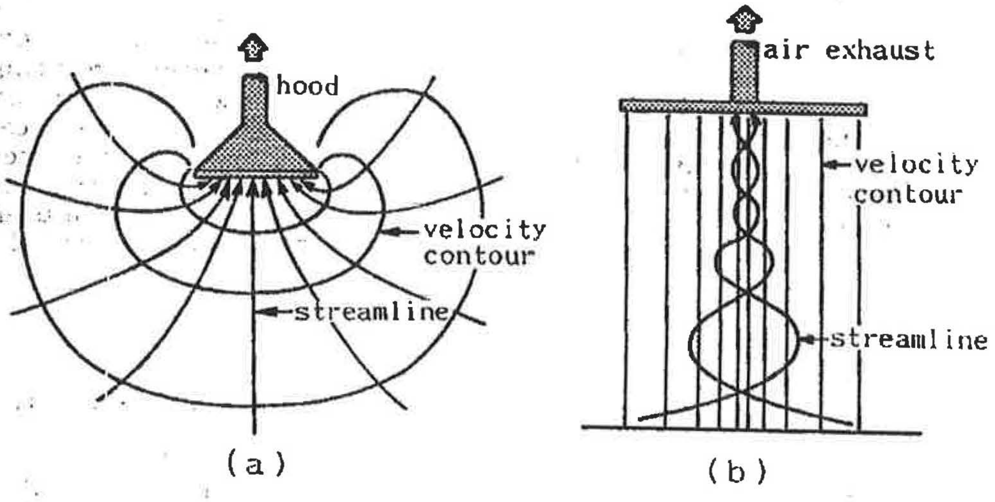


Fig. 1. Rankine vortex. Tangential velocity component and static pressure distribution.



(a) (b)

Fig. 2. Comparison of streamlines and velocity contours around a local exhaust hood (a) with those in a spiral vortex flow (b).

In a flow such as the Rankine vortex, air flows in a spiral into the core of low static pressure, hence most of the air contaminants are also concentrated in the core. In comparison to the conventional method of a local exhaust ventilation, using a hood as an example (Fig.2), the spiral vortex method has the following characteristics.

- Air contaminants far from the exhaust outlet can easily be collected and removed because the air velocity at the core does not significantly decay even at points away from the air outlet.
- Ventilation can be achieved efficiently with less air volume, because air contaminants are concentrated in the vortex core and transported to the exhaust outlet along the core axis.
- Because air contaminants always flow into the core, they can be kept from diffusion to the space around the core, and there is little possibility of neighbors beeing exposed to the contaminants.

Conditions for Forming Spiral Vortex Flow in Buildings

The simplest way to form a spiral vortex in a building is to generate circular airflow along the walls by using a supply airflow and to provide an exhaust outlet in the ceiling near the center axis of the rotational flow. If a horizontal vortex is desired, one can be obtained by generating a horizontal rotational airflow and providing one or two exhaust outlets in the walls near the center axis of the rotational flow. In conventional design for indoor air quality control, it is generally known that the location of exhaust openings do not play an important role. However, in planning indoor air quality control using a spiral vortex flow, the location of the air exhaust outlet is critical.

For the successful design of a ventilation system using a spiral vortex flow in variously shaped spaces in buildings, it is necessary to produce a vortex at a specified position and a specified strength, and to maintain the flow in a stable condition. Parameters relating to the design are the geometry of the indoor space (i.e. the plan and cross section) and the roughnesses of the surrounding surfaces caused by exposed pillars, beams, lighting devices, furnishings and the presence of people. Also important are the thermal effects caused by the heat which is generated inside the room or transfered from the outside. The influence of these must be synthetically assessed and integrated into the design method.

Application of Spiral Vortex to Local Exhaust Ventilation

Studies of spiral vortex flow application to local exhaust ventilation have been reported by Ljungovist, B. and Waering, C. (1), and the authors (2). In this paper, we intend to present an overview of a localized exhaust system, which represents recent improvements over the method previously reported by the authors.

Figure 3 shows the outline of the system. It consists of four independent columns, each of which has several air inlets in the form of a slot arranged orthogonal to each column, and a table having an air exhaust opening at its center. Air flowing from the inlet slots forms four air curtains, which then combine themselves into a vortex flow, which exits through the exhaust outlet at the center of the table, after flowing into the core formed in the vortex center. Thus, air contaminants generated in the region surrounded by the four columns are concentrated into a core in the vortex center and exhausted without being dispersed beyond the confined region. Photo 1 shows how contaminants are concentrated.

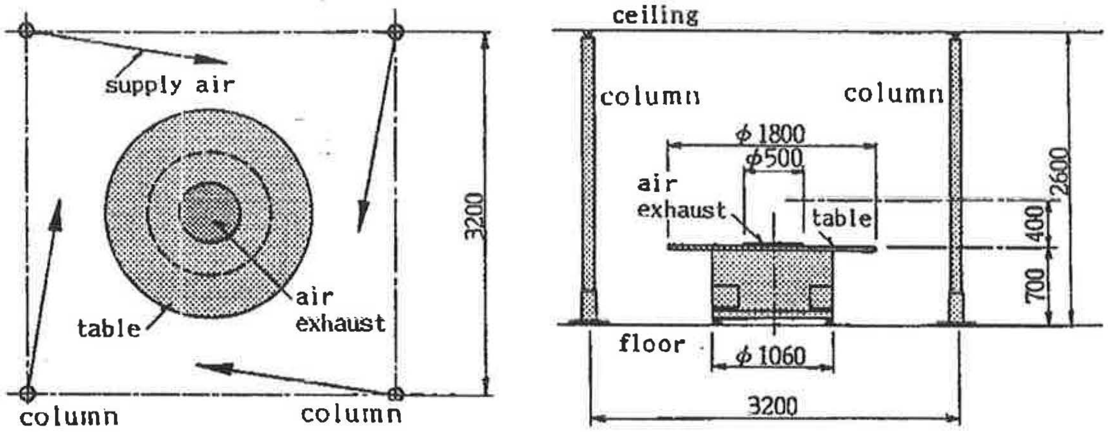


Fig. 3. A spiral vortex flow generating system for local exhaust ventilation. It consists of four independent columns, each of which has air inlets in the form of a slot, and a table having an air exhaust opening at its center.

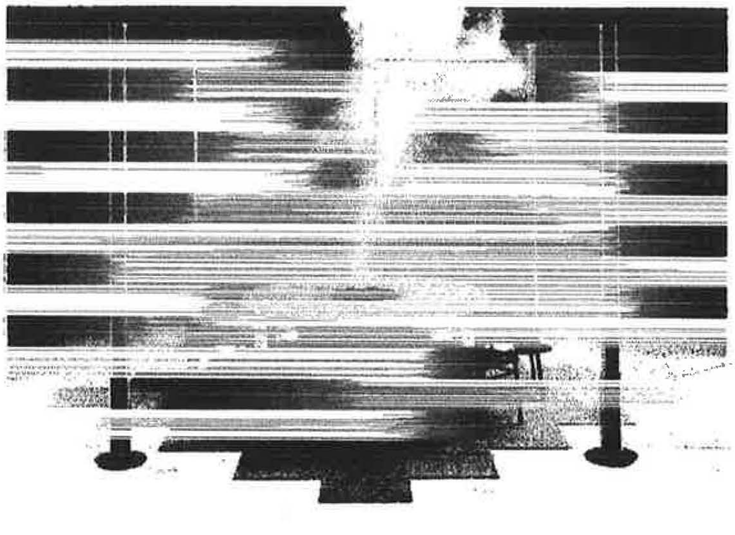


Photo 1. Visualization of air contaminant behavior in a local exhaust ventilation system utilizing a spiral vortex flow.

Installation of this system in a smoking area in a building, for example, would prevent cigarette smoke from diffusing to the outside of the confined smoking area. In order to confirm this effect, an experiment was carried out by installing the system in a room for which no mechanical ventilation was provided, as shown in Fig. 4 . For the experiment, the volume of inlet air was 6.5 m^3/min per column, the mean velocity of airflow at the slot openings was 3.5 m/s, and the range of airflow velocity in the smokers' vicinity was 0.18 to 0.36 m/s. Figure 5 shows the results of measurements of particle concentration in and out of the system when six smokers seated at the table smoked one cigarette each simultaneously, taking 4.5 minutes to finish it. The results indicate that diffusion of cigarette smoke can be prevented to a considerable degree.

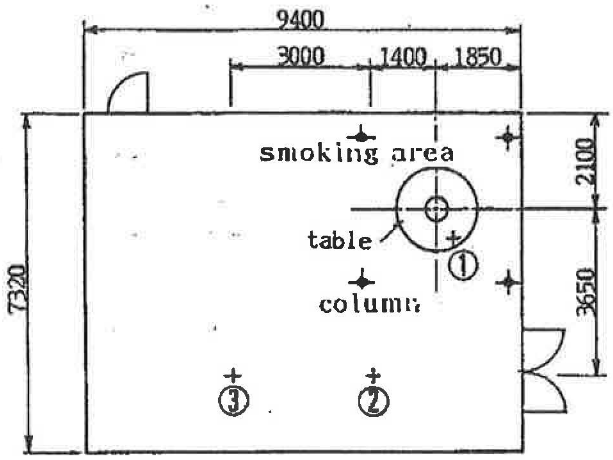


Fig. 4. Installation of a spiral vortex local exhaust system in a test room for which no mechanical ventilation was provided. ①, ② and ③ are measuring points.

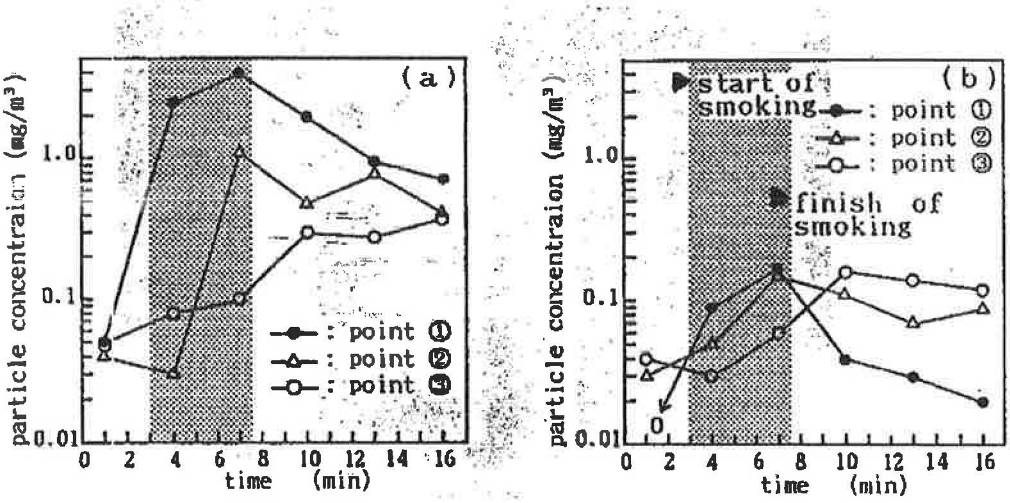
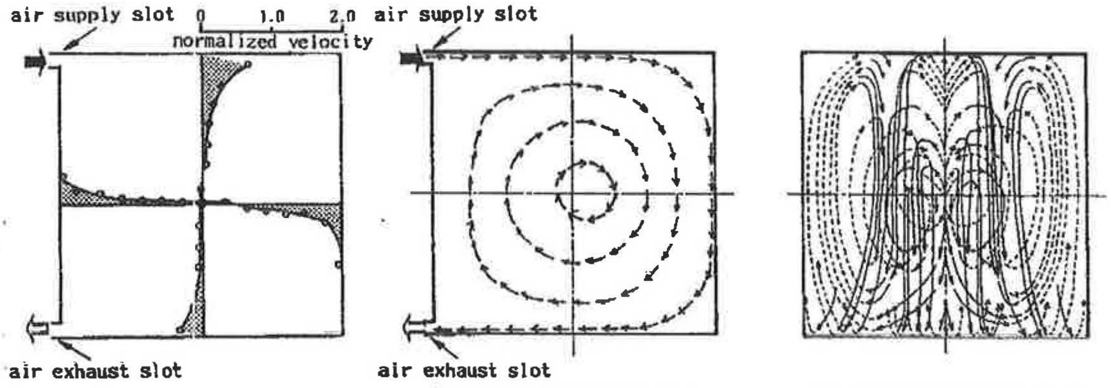


Fig. 5. Comparison of particle concentrations at three measuring points. (a) Spiral vortex system was not in operation. (b) Spiral vortex system was in operation.

Velocity and Concentration Distribution in Spiral Vortex and Simple Circular Flows Formed in Buildings

Experiments on a Cubic Model

A first experimental study was conducted to artificially produce a spiral vortex flow in a building space, and to observe the behavior of air contaminants in it. The model is a near cube (L=730mm, W=700mm and H=700mm) having an air supply slot (L=700mm and H=28mm) measuring the full width of the room mounted on the highest part of the front wall. To produce a spiral vortex and a simple circular flow, two types of exhaust outlets were provided; a circular hole in the center of a side wall for the spiral vortex flow, and a slot on the lowest part of the front wall for the simple circular flow.

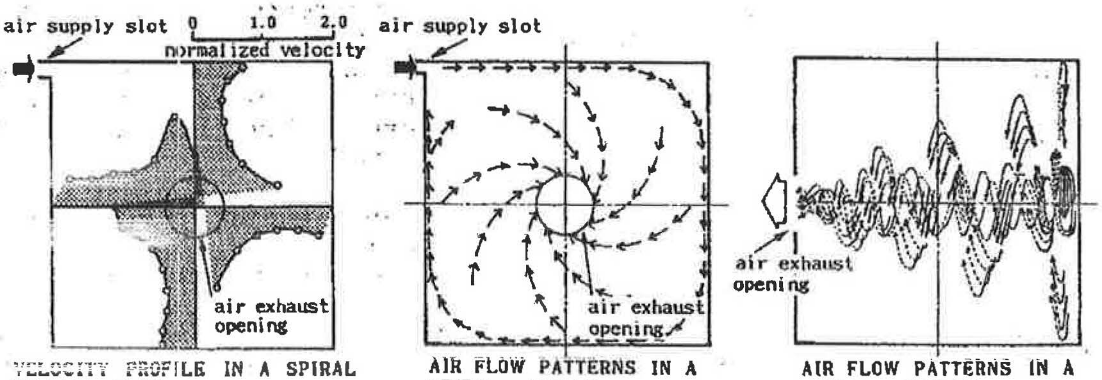


VELOCITY PROFILE IN A COMMON VORTEX FLOW.

AIR FLOW PATTERNS IN A COMMOM VORTEX.

AIR FLOW PATTERNS IN A COMMOM VORTEX.

Fig. 6. Velocity profiles and airflow patterns in a cubic model under isothermal conditions. Simple circular airflow with slots for both air intake and outlet. Volume of intake air, 1.72 m^3/min.



VELOCITY PROFILE IN A SPIRAL VORTEX FLOW.

AIR FLOW PATTERNS IN A SPIRAL VORTEX.

AIR FLOW PATTERNS IN A SPIRAL VORTEX.

Fig. 7. Velocity profiles and airflow patterns in a cubic model under isothermal conditions. Spiral vortex airflow with a slot for air intake, and a circular hole for outlet. Volume of intake air, 1.72 m^3/min.

Figures 6 and 7 show the airflow patterns and velocity profiles. In the case of spiral vortex flow, the velocity in the vicinity of the vortex core formed at the center of the vortex was considerably high, and airflow in a typical spiral shape was observed. Also, the static pressure at the vortex core, based on the dynamic pressure at the air supply outlet, is lower compared to the static pressure in the surrounding zone by a magnitude of about fifteen.

Figures 8 and 9 show the measurement results of the concentration distribution of a tracer gas (ethylene). In a spiral vortex flow, air contaminants released in the vicinity of the core are barely diffused externally, and are, instead, transported to the air exhaust outlet along the core axis. Furthermore, air contaminants released in the outer zones of the vortex are funnelled gradually toward the vortex core by the spiral airflow. Consequently, the concentration at the core becomes the highest, and a series of concentration contours are formed around the core. In a simple circular airflow, on the other hand, air contaminants generated in the center zone of the airflow are diffused widely almost throughout the room.

Experiments on a Scale Model of a Large Dome

To confirm the practical applicability of a spiral vortex flow in the ventilation and air conditioning of buildings, experiments were conducted on a scale model of a large dome with 10,000 seats in upper and lower levels. Air volume flow rate and heat generated by an audience of 10,000 were estimated to be 500,000 m^3/hr. and 450,000 W, respectively. The experiments concentrated on determining an improvementin the discharge effect of air contaminants compared to the simple circular airflow method. For convenience, in the present experiments a tracer gas (ethylene) was used to represent the air contaminants.

Figure 10 shows the experimental model setup on a one-fiftieth scale. The model is made of plywood, with external surfaces covered in glass wool (50mm thickness). Twenty multi direction nozzles were installed in the rear wall behind the seats on each level. To generate a circular airflow, the nozzle attachment surfaces are set at a 25 degree angle to the tangential derection of the circumference, but are not tilted relative to the vertical direction. An outlet mounted at the top of the dome was used for air exhaust to produce a spiral vortex flow. For a simple circular airflow, twenty openings located at regular intervals in the floor near the lower level seats were utilized as air exhaust openings.

In these experiments, only human heat generated by the audience was considered as the heat load, which was provided by electric heaters located in the audience seating area. As a parameter for similarity of air distribution in the scale model and a full-size structure, the Archimedes number was taken into consideration. Due to various experimental constraints, the supply air velocity was selected at 0.24 times relative to full-scale velocity. Consequently the Reynolds number at the air supply opening was approximately 1,800.

Figure 11 shows the results of air velocity measurements taken at each representative height in the plane of the center cross section of the dome model. In the case of simple circular flow, velocity decreases

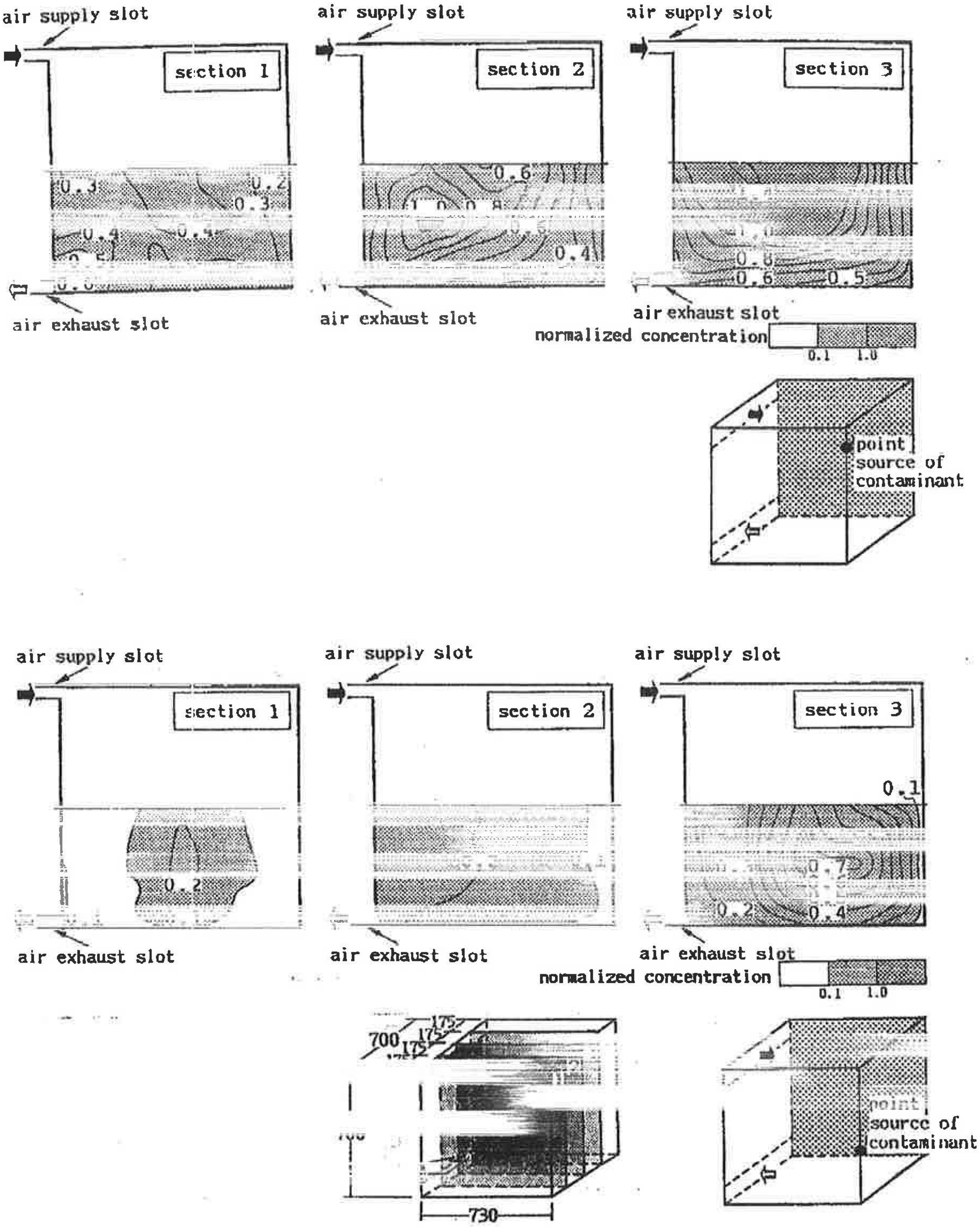


Fig. 8. Normalized concentration distributions in a cubic model under isothermal conditions. Simple circular airflow with slots for both air intake and outlet. Volume of intake air, 1.72 m³/min.

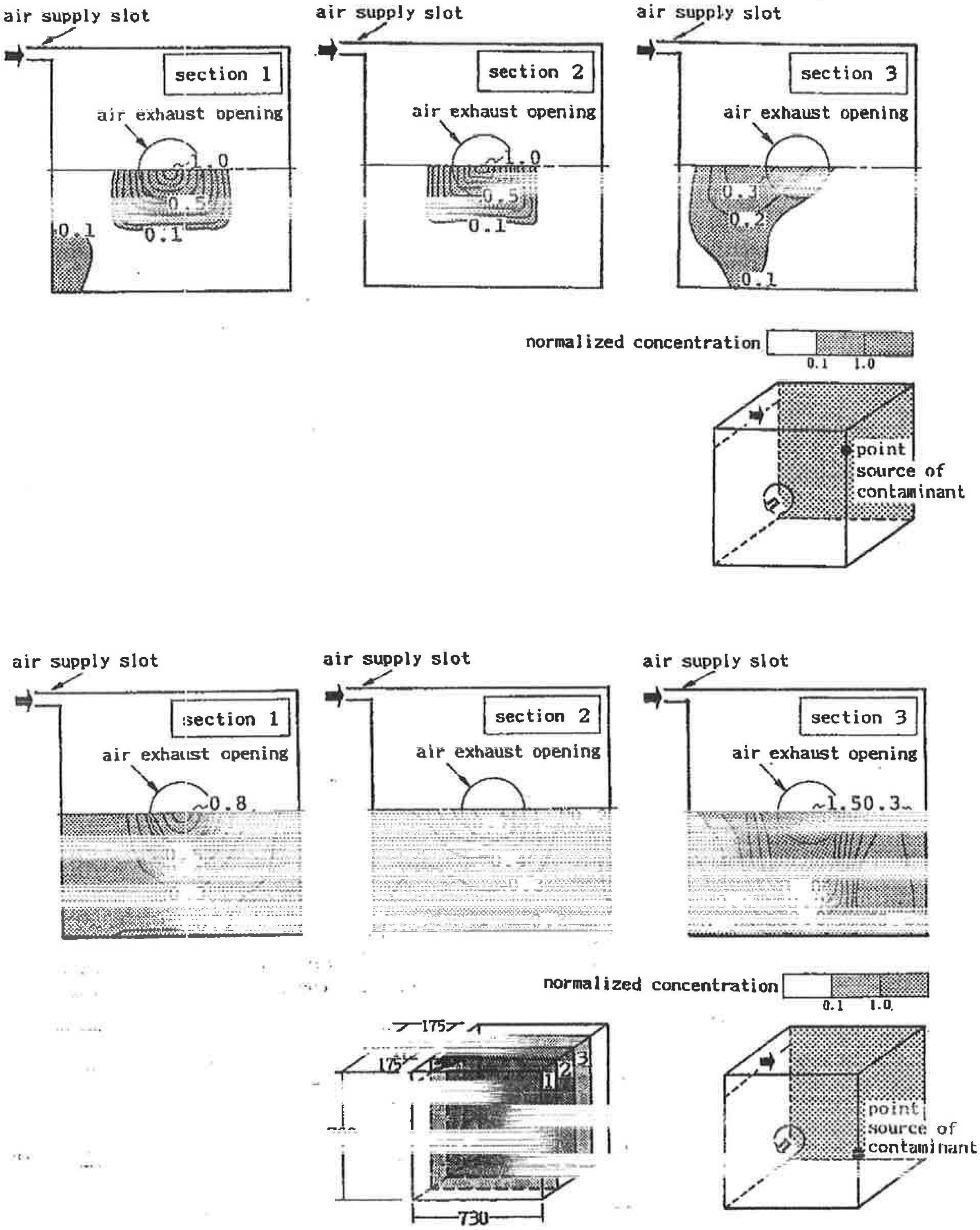


Fig. 9. Normalized concentration distributions in a cubic model under isothermal conditions. Spiral vortex airflow with a slot for air intake, and a circular hole for outlet. Volume of intake air, 1.72 m³/min.

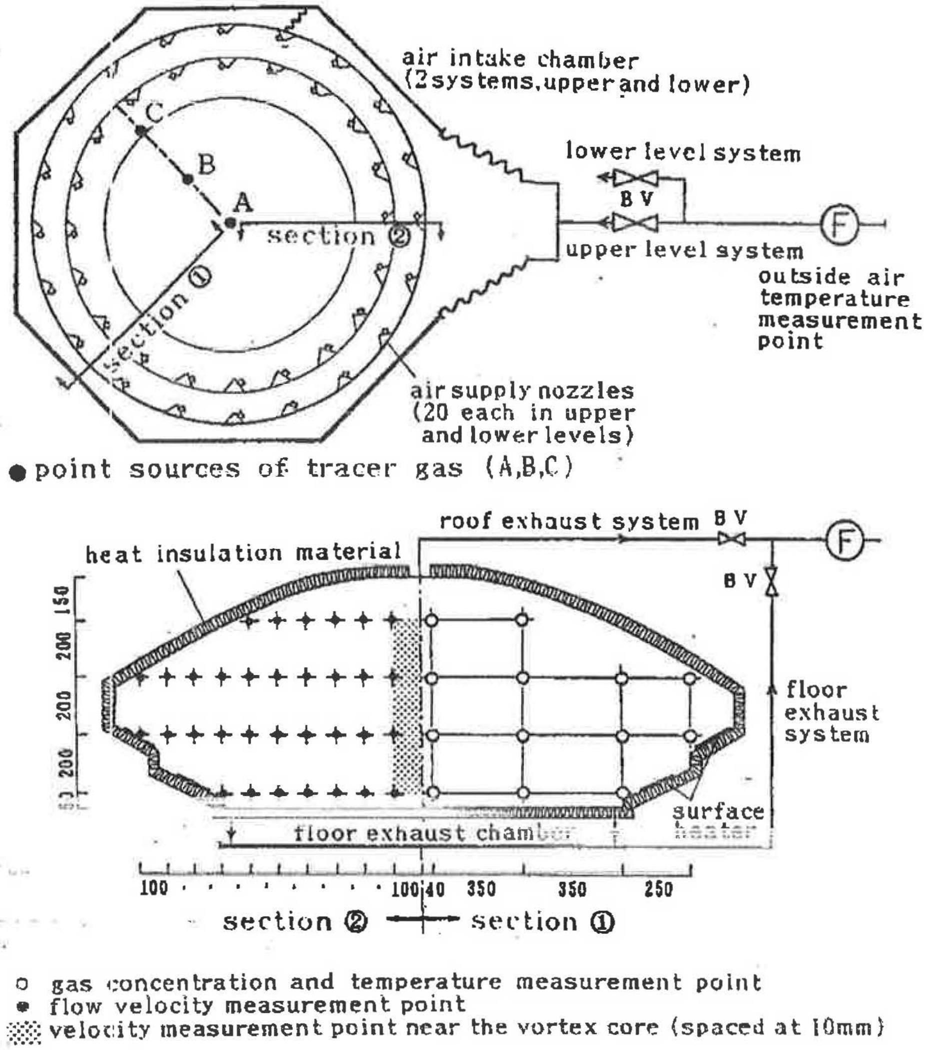


Fig.10. Scale model and experimental setup for a large dome.

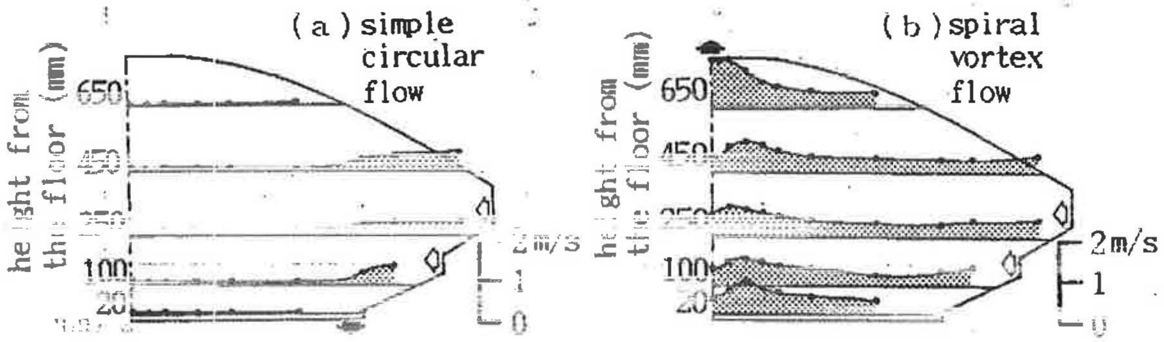


Fig.11. Velocity profiles in a cross-section. (a) Simple circular airflow. (b) Spiral vortex airflow.

considerably toward the center zone, although air velocity is high in the peripheral zone of the circular flow in the dome, because this zone falls in the region of air blowout. In contrast, a spiral vortex flow maintains high velocities throughout all the zones in the dome, reaching, in particular, a maximum velocity value in the center zone, where the core exists. This tendency is in agreement with the experimental results using a cubic model, as mentioned before. Note that these values were measured using an omniderectional anemometer, and are in absolute velocity values.

Figure 12 shows the results of velocity component measurements taken in and around the core for the purpose of better understanding spiral vortex flow characteristics using a split-film anemometer. The tangential velocity component takes its maximum value at the core boundary and then decreases to almost zero on the center axis of the core. The maximum value increases as the height from the floor increases. On the other hand, the axial velocity component reaches its maximum value on the center axis of the core at any height from the floor.

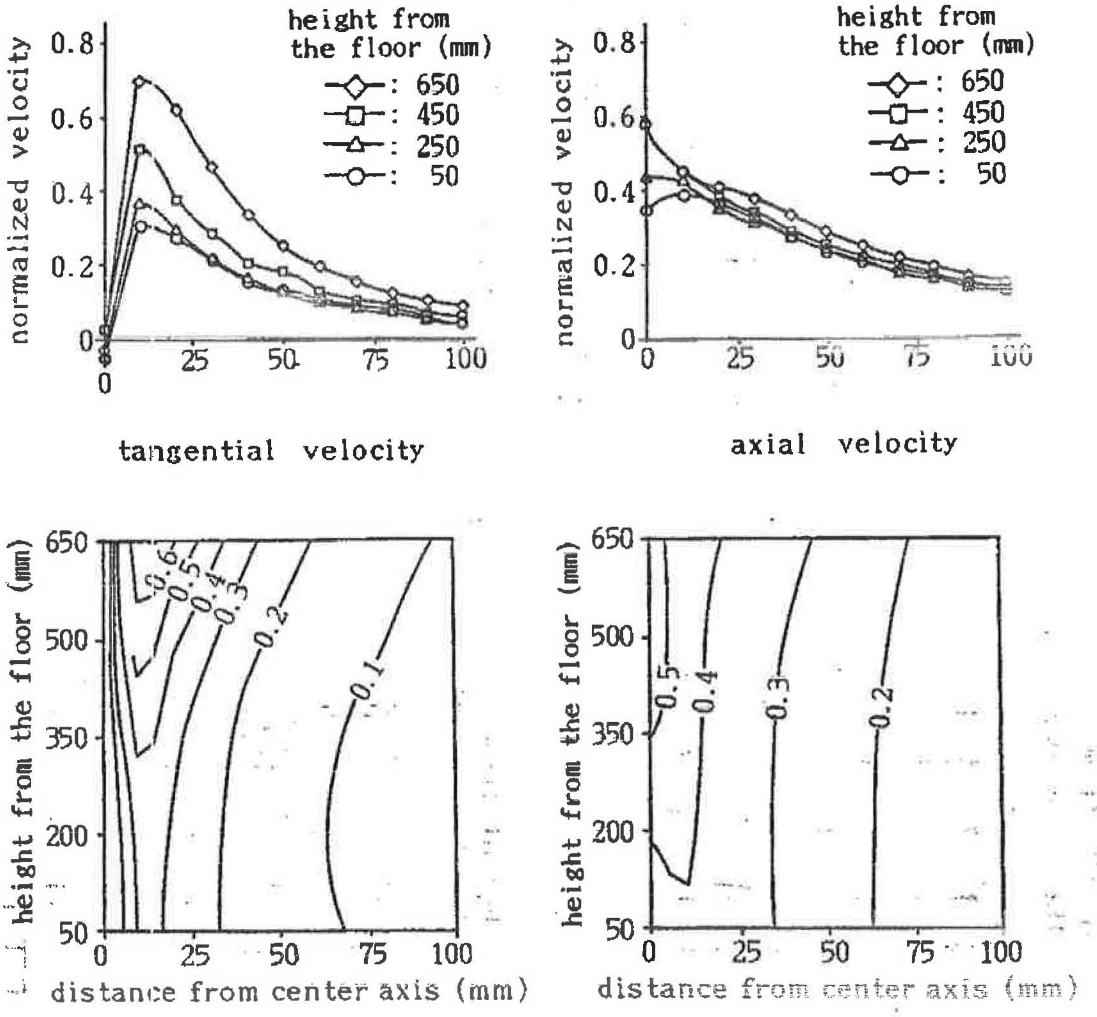


Fig.12. Measurement results of tangential and axial velocity profiles and contours at the center of a spiral vortex.

Depending on the type of building, there are cases where application of the vortex core system is not desirable, in which the air velocities are high near the floor level. As a method to prevent this, a circular plate may be provided to receive the core at a suitable height in the vortex center. Figure 13 shows the results of velocity vector measurements taken in the regions above and under the circular plate. It can be seen from the figure that a spiral vortex flow was formed above the circular plate having a core in its center, where the velocities are high, while under the plate, a simple circular flow is generated with low velocities in its center region.

Figure 14 shows the concentration distribution measured in a plane rotated 90 degrees to the wind direction from the point source of air contaminant generation. The concentration values in the figure are shown as relative concentrations with reference to the concentration value at the exhaust outlet. In the case of simple circular flow, the

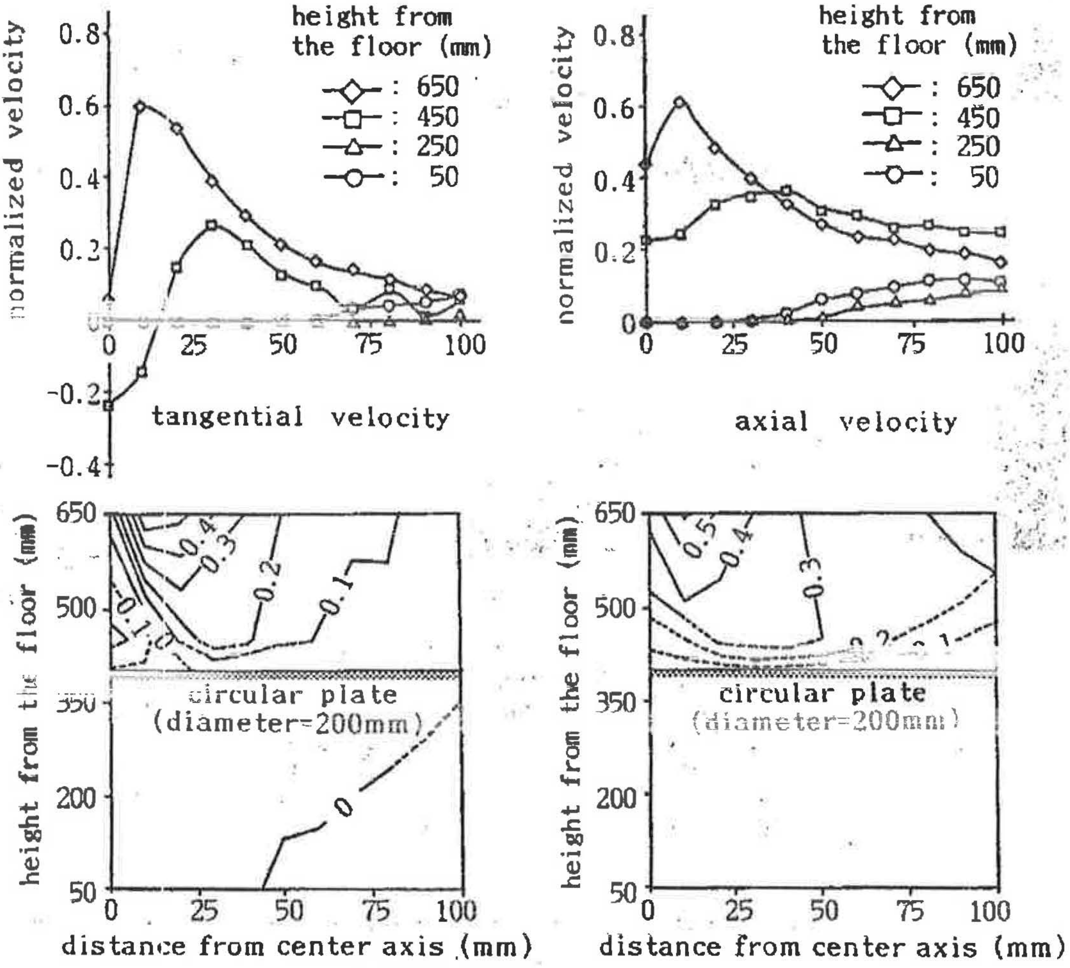


Fig.13. Measurement results of tangential and axial velocity profiles and contours at the center of a spiral vprtex. A circular plate is provided to receive the core in the vortex center.

concentration reaches high values across a wide range if the source of contaminant generation exists in the vicinity of the circular flow center, while there is less diffusion of contamination if the source of contaminant ganeration is in the periphery of the circular flow, due to the proximity of the source to the exhaust outlet. In the case of a spiral vortex flow, diffusion of contamination in the peripheral zones is limited when the source of contaminant generation is in the vicinity of the vortex center, and the contaminants are transfered in a vertical direction upward to the exhaust outlet. In this case, the contaminants are concentrated toward the core at the vortex center and exit riding on the spiral airflow.

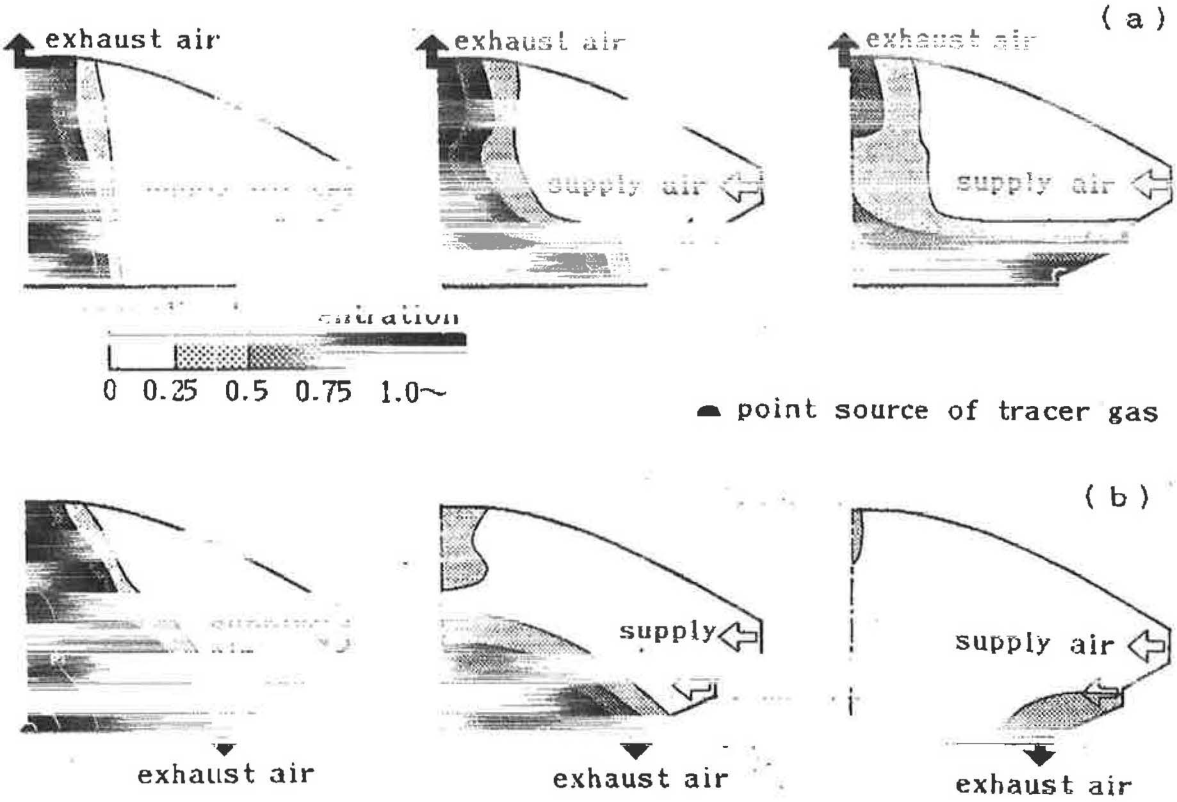


Fig.14. Normalized gas concentration distribution in a cross section rotated 90 degrees to the wind direction from the source of gas generation. Measurements were taken two minutes after the start of gas generation. (a) Air exhaust openings were located in the floor near the lower level seats. (b) An air exhaust opening was mounted at the top of the roof.

The above results were obtained from measurements taken two minutes after the start of contaminant generation. As for the variation of concentration across time, Fig. 15 shows an example of the concentration values at the exhaust outlet in the case of a spiral vortex flow. The concentration distribution in the dome model measured thirty seconds after the stoppage of contamination generation is shown in Fig. 16. The decay in concentration in a simple circular flow system is considerably slow when the position of the contaminant generation source is in the center

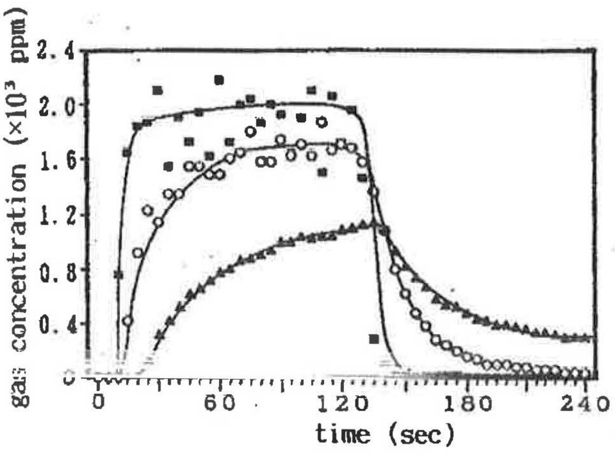


Fig.15. Time series variation of gas concentration in exhaust air. An air exhaust opening was mounted at the top of the roof. Source points of gas generation (■ ;A, ○ ;B, ▲ ;C).

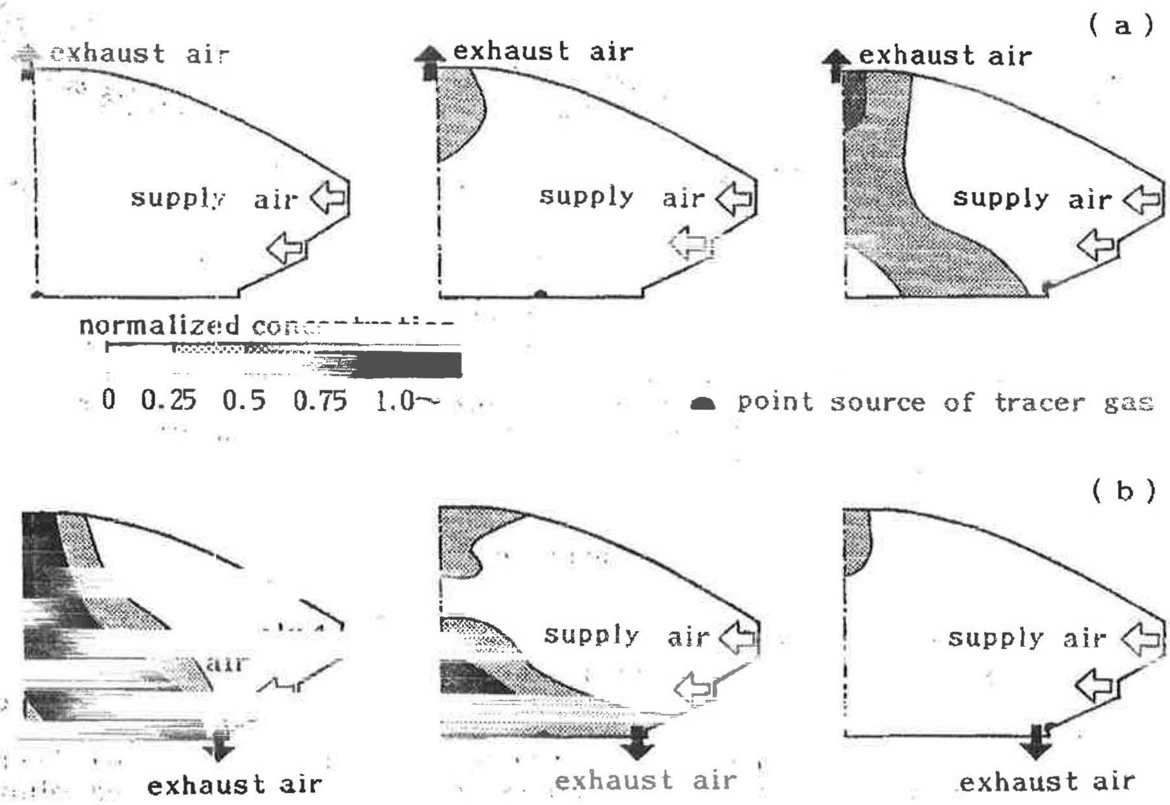


Fig.16. Normalized gas concentration distribution in a cross section rotated 90 degrees to the wind direction from the source of gas generation. Measurements were taken thirty seconds after the stoppage of gas generation. (a) Air exhaust openings were located in the floor near the lower level seats. (b) An air exhaust opening was mounted at the top of the roof.

region of the circular flow, and there is a tendency to build up residual concentration in two zones, one near the exhaust outlet and the other close to the roof top. In the case of a spiral vortex flow, however, the contaminants are always concentrated at the core of the vortex center and are exhausted regardless of the location of the contaminant generation source, and the contaminants are exhausted faster as the source of contaminant generation is located closer to the center.

Figure 17 shows concentration distribution when a circular plate (diameter-200 mm) was installed in the space at the center of the dome in an attempt to confine the core formation to the upper part of the dome. It is apparent that the circular plate affects neither the concentration distribution or its variation across time to any great extent. Installation of such a circular plate, however, permits the characteristics of a spiral vortex flow to be utilized in removing air contaminants without generating high air velocities near the floor surface.

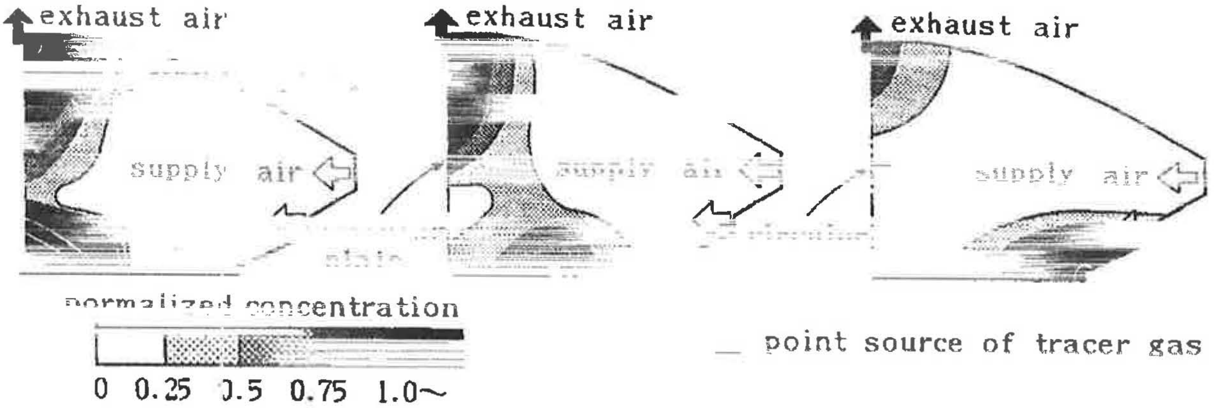


Fig.17. Normalized gas concentration distribution in a cross section rotated 90 degrees to the wind direction from the source of gas generation. A circular plate was provided to receive the core in the vortex center. Measurements were taken two minutes after the start of gas generation.

Conclusions

Preliminary experiments have been conducted regarding the feasibility and limits of utilizing spiral vortex flows in indoor climate control. As for the utilization of spiral vortex flows in localized ventilation, there have already been some examples of practical applications, and a number of effective application methods have been proposed. On the other hand, many topics remain to be studied regarding practical applications of spiral vortex flows to the ventilation and air conditioning of entire building spaces due to the complexities of shape and function of the spaces. The authors intend to investigate the areas outlined below in future studies.

-The effect of the overall space configuration (such as the horizontal and cross sectional shapes of rooms) on the formation of

a spiral vortex flow.
- The effect of the roughness of the surrounding surfaces and the effect of the presence of structural members and furnishings in space on the formation of a spiral vortex flow.
- The effect of thermal convection on the formation of a spiral vortex flow.
- A study for avoiding vortex core formation in the occupied zone.

References

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SUMMAR Y

This paper provides a brief overview of the characteristics of spiral vortex flow, which is a novel approach to the fields of ventilation and air conditioning. This is followed by an introduction of a successful example of a practical, localized ventilation system which utilizes the spiral vortex flow formed by a combination of air curtains blown out of air supply openings provided in four independent columns. Finally, the results of two model experiments assessing application of spiral vortex flow in the ventilation of entire spaces are presented. One experiment was designed to observe airflow patterns, measure airflow velocities, and to compare the modes of air contaminant diffusion in the respective cases of spiral vortex flows and ordinary circular flows formed in a simple cubic model. The second was a model experiment conducted within a large domed space capable of seating 10,000 people. Characteristics that were previously unrecognized in conventional ventilation systems were revealed from the results of these experiments, including the method of spiral vortex flow formation in a building space, velocity component and pressure distribution in vortices, the behavior of air contaminants in vortices, and other phenomena.