

DEVELOPMENT OF THE SWIRLING INDUCTION TYPE DISPLACEMENT HVAC SYSTEM FOR LARGE ENCLOSURES

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ABSTRACT

The ordinary displacement ventilation system (DV) needs large installation spaces for large supply diffusers with lower supply air velocity to avoid the draft discomfort at the foot level, and large supply air volume to control allowable vertical temperature gradient within the occupied zone. Furthermore, the DV is difficult to heat without other warming means in the winter. The swirling induction type HVAC system (SWIT) was developed as utilizing a compact air diffuser increasing the induction function by means of swirling air jets. Features of the SWIT are to increase the induction effect on the surface of SWIT air diffusers, to reduce the supply air velocity, to circulate air in the occupied zone at cooling in the summer, and to induce cold air mass from the occupied zone with low velocity at heating in the winter. This paper was summarized measurement results of ventilation effectiveness and temperature distribution in the summer and the winter, and compared with an ordinary displacement system and mixing system. Furthermore, we estimated energy conservation of the SWIT by comparing with the mixing system for an industrial plant on a scale of 20,000 m².

KEYWORDS

Thermal Comfort, Ventilation Effectiveness, Energy Conservation, Displacement Ventilation

1. INTRODUCTION

HVAC systems have to satisfy demands of thermal comfort, energy conservation and IAQ. AT first, features and subjects of an ordinal mixing system (MIX) and a conventional displacement system (DV) which are two typical HVAC systems are shown as follows.

The MIX conducts the whole space air in the large enclosure by high speed air supply diffusers at a ceiling. The MIX takes much cooling energy because the supply air is mixed with warm air at ceiling. Moreover at heating, warm supply air is difficult to reach to an occupied zone because of buoyancy, and the cold air in the occupied zone can't get warm easily.

The DV is able to fill an occupied zone with cool and clean air and rise up natural convection currents and contaminants from tooling machines toward the ceiling by buoyancy effect. However, the DV has to supply air at slower below 0.2 m/s¹) to avoid the draft discomfort at foot level. From these reasons, the DV requires to install bigger air diffusers within the occupied zone, and to supply larger air volume to maintain allowable temperature gradient within the occupied zone. In the DV, air movement is limited to a floor level by cool supply air and natural convection currents by heat sources. Although the contaminants emitted from heat sources are exhausted at ceiling quickly, the contaminant emitted from without heat sources is difficult to be dilute in the DV. And especially, the DV has a problem at heating as difficult without other heating devices.

As so, the swirling induction type HVAC system (SWIT) was developed as utilizing a compact air diffuser increasing the induction function by means of swirling air jets. Features of the SWIT are to increase the induction effect on the surface of SWIT air diffusers, to reduce the supply air velocity, to circulate air in the occupied zone at cooling in the summer, and to induce cold air mass from the

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occupied zone with low velocity at heating in the winter. Therefore, the temperature distribution within the occupied zone can be equalized with smaller supply air volume and removed contaminated air from the occupied zone by the use of buoyancy effect.

We measured the ventilation effectiveness and temperature distribution in the summer and the winter, and verified the characteristic of the SWIT basing on comparison with the DV and the MIX. Furthermore, we estimated annual energy consumption and compared energy conservation with the MIX.

2. METHODS AND MEASUREMENTS

The SWIT air diffuser with size of $0.6m^W \times 0.6m^D \times 2.1m^H$ and the DV air diffuser with size of $0.96m^W \times 0.56m^D \times 2.1m^H$ were respectively installed on the floor level of machine shop building with area of $190 m^2$ and ceiling height of 10 m. MIX which were installed nozzle diffuser with diameter of 0.5 m at a height of 4 m in the machine shop. Each air volume supplied from SWIT, DV and MIX was controlled at set point of $21 m^3/(hm^2)$, that is, the air change rate was 2 times/h and the supply air temperature was $18^\circ C$ at cooling, and $30^\circ C$ at heating. We picked up measuring data when the outdoor temperature was equal to $30^\circ C$ at cooling and $10^\circ C$ at heating to compare with each characteristic under same condition. The indoor cooling load during the test was $78 W/m^2$, that is, $37 W/m^2$ from tooling machines plus $41 W/m^2$ from ceiling mercury lamps. The indoor sensible heat load including the outside wall load during the test was $120 W/m^2$ at cooling and $-50 W/m^2$ at heating.

Figure 1 shows the contour of the actual testing space, the placement of generating heat load from tooling machine and the measuring points. The comparison between the ventilation effectiveness of each system was measured by the tracer gas (SF_6+He) adjusted to air density as contaminants and evaluated the difference in diffused states of the contaminants. We set two dosing points of the tracer gas. One point was directly above tooling machines (H3) where the machine frame heated up during operating, and the other point was a location of the point B (FL+1m) without heat generation. Table 1 and Table 2 show measured data in the summer and the winter respectively.

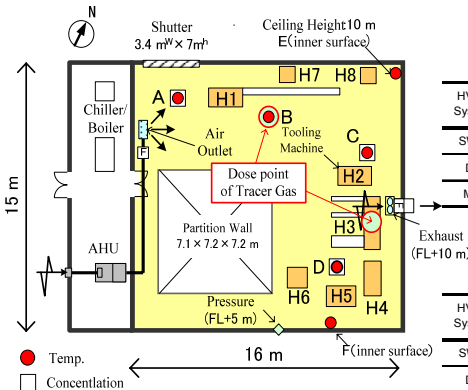


Figure 1. Measuring Points in a Machine Shop

Table 1. Measured Data in the summer

HVAC System	Outdoor Temp. [°C]	Supply Air Vol. [m³/h]	Supply Vel. [m/s]	Supply Temp. T _s [°C]	Exhaust Air Temp. T _e [°C]	T _e -T _s [°C]
SWIT	30.1	4,119	1.0	18.2	35.3	17.1
DV	30.1	4,055	0.3	17.8	34.7	16.9
MIX	30.2	4,046	5.7	18.0	33.8	15.8

Table 2. Measured Data in the winter

HVAC System	Outdoor Temp. [°C]	Supply Air Vol. [m³/h]	Supply Vel. [m/s]	Supply Temp. T _s [°C]	Exhaust Air Temp. T _e [°C]	T _e -T _s [°C]
SWIT	10.1	3,982	0.9	29.9	22.3	-7.6
DV	10.0	3,992	0.3	29.7	22.8	-6.9
MIX	10.1	4,016	5.7	29.7	22.1	-7.6

3. RESULTS & DISCUSSIONS OF THERMAL COMFORT AND VENTILATION EFFECTIVENESS

3-1 Thermal comfort during cooling

Each airflow pattern by the DV and the SWIT is shown in Photo.1 and Photo.2, respectively. The airflow of the DV is dropped to the foot level due to the density difference. The other hand, the airflow of the SWIT is able to provide the cooled air not only below the legs, but also at the height of the SWIT air

diffuser. Figure 2 shows a typical vertical temperature distribution at point C. The SWIT can form thermal stratification and maintain lower temperature zone within the occupied zone less than the height of ca. 2 m on comparing with the MIX. The SWIT is also able to possess a smaller vertical temperature gradient within the occupied zone than the DV. Figure 3 shows the comparison the thermal comfort at 1 m above floor level at points A to D, utilizing the PPD as a general marker for making evaluation from information on the temperature, humidity, air speed, radiant temperature, amount of clothes, and metabolic figure. The clothing amount was 0.5 clo and the metabolic figure was 1.2 met. The SWIT is able to estimate lower PPD and superior comfort at all points than the other.



Photo. 1. Airflow pattern of the DV

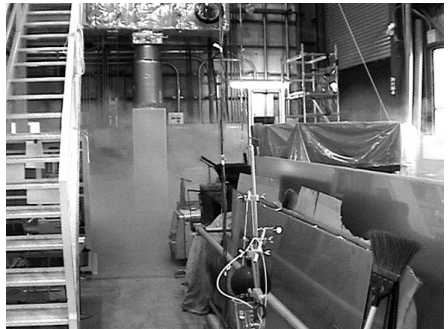


Photo. 2. Airflow pattern of the SWIT

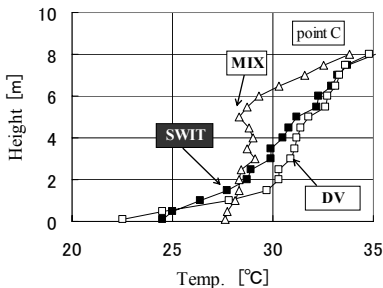


Figure 2. Vertical Temperature Distribution in the summer

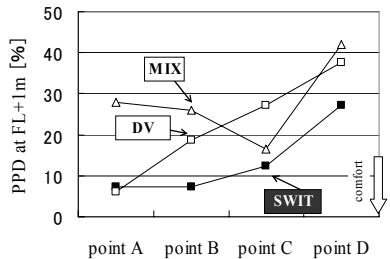


Figure 3. PPD Distribution at Occupied Zone in the summer

3-2 Ventilation effectiveness during cooling

Figure 4 shows the average concentration of the tracer gas from 0.1 m to 2 m above the floor at points A to D, and the nominal concentration in the occupied zone, that is, the ratio of average concentration within occupied zone to concentration of perfect mixing. The left bar graph is the results in the case with heat source (dose at H3), while the right bar graph without heat source (dose at point B). The concentration of the tracer gas at each measurement point is an average value for 30 minutes as the sampling time of approximately 30 seconds.

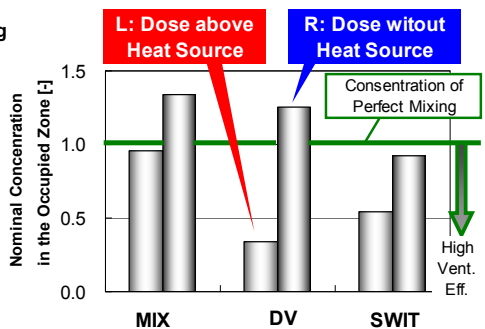


Figure 4. Nominal Concentration in Each Case Dosing Point

SHASE ventilation standard requires raising or lowering the outdoor air requirements according to the nominal concentration in the occupied zone²⁾. As shown in Figure 4, among three systems being compared, only the SWIT was able to maintain the nominal concentration in occupied zone below the full mixed concentration regardless of whether there was a source of heat at the emission point of contaminant.

3-3 Thermal comfort during heating

Figure 5 shows a typical Vertical air temperature distribution at point C by these 3 systems. The SWIT was able to maintain at the foot level temperature warmer by 2°C than other systems. The SWIT was able to increase the actual circulating air volume more than other systems within the occupied zone. Figure 6 shows the PPD during heating at 1 m above the floor at the points A to D. The clothing amount was 1.0 clo and the metabolic figure was 1.2 met. During this heating, the SWIT had a lower PPD and superior comfort at all points of A to D in the winter.

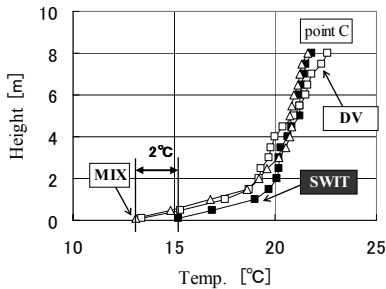


Figure 5. Vertical Temperature Distribution in the winter

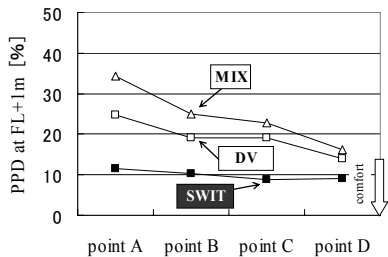


Figure 6. PPD Distribution at Occupied Zone in the winter

3-4 Ventilation effectiveness during heating

Figure 7 shows the distribution of the normalized tracer gas concentration by the SWIT and the MIX when the tracer gas was dosed at 1 m above point B. Each measured concentration was normalized by using of the concentration at the exhaust air to represent by the dimensionless value. The MIX was not able to move the air within the occupied zone during heating and the dosed tracer gas within the occupied zone was not able to be diluted. So that, the tracer gas concentration at the point C was higher as 7 times of the exhaust concentration. The other hand, the SWIT was able to remove the cold air within the occupied zone, so that, fully move the air within the occupied zone during heating.

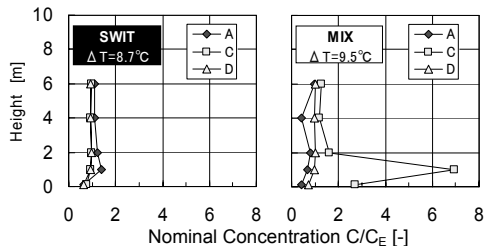


Figure 7. Nominal Concentration in the winter (Dose without Thermal Load)

4. RESULTS & DISCUSSIONS of ENERGY CONSERVATION

4-1 Conditions for Estimation

We estimated the energy conservation of cooling peak load and annual energy consumption in the SWIT by comparing with the MIX which had the temperature difference between supply air and exhaust

air by 10°C. Table 3 shows estimation conditions of HVAC devices for an industrial plant on a scale of 20,000 m². Table 4 shows operating conditions for both HVAC systems. The heat transfer rate of walls was set at 2 W/(m²K). The outdoor air volume of the MIX was set at 50 % of the supply air volume. The SWIT is able to be larger than the MIX on the temperature difference between supply air and exhaust air, so that, the supply air volume is able to be smaller than the MIX. The SWIT is able to allow lowering the outdoor air volume because of high ventilation effectiveness. However, we gave the following conditions: SWIT is operated in all outdoor air through the year, and that volume is not less than the MIX. Supply air temperature for SWIT is above 16°C. Also, the vertical temperature gradient within the occupied zone of the SWIT is set to 3°C/m or less. The room temperature at 1.1m above floor level is controlled design temperature by both systems. The MIX was assumed as perfect mixing which has no vertical temperature difference.

Table 3. Design Conditions of HVAC Devices

Chiller's COP	4.5
Boiler Efficiency	90%
Fan Efficiency	50%
Pump Efficiency	60%
Fan Pressure	800 Pa
Pump Pressure (first)	250 kPa
Pump Pressure (second)	500 kPa
Cooling Pump Pressure	200 kPa

Table 4. Design Conditions of Air Temperature

Outdoor Air Condition of Summer Peak	33.4°C, 18.7g/kg(DA)
Data base of Outdoor Air	Micro Peak (Tokyo) (Average for each hour)
Room Temp. (Jun~Sep.)	28°C
(Apr./May./Oct./Nov.)	23°C
(Dec.~Mer.)	18°C
Operation Time	8:00~18:00

4-2 Peak load reduction rate at cooling

Figure 8 shows the results of the comparison on energy consumption at peak outdoor air condition in cases of indoor cooling loads between 50 and 200 W/m². Figure 8 shows, as long as more indoor cooling load, the SWIT is more efficient on energy conservation than the MIX. The SWIT was able to reduce 32% on the energy consumption for air-conditioning at an indoor cooling load of 100 W/m² than the MIX.

The supply air volume of the SWIT was approximately 50% of the MIX for each indoor cooling load. Then, the energy consumption of fans in the SWIT was half of the MIX. The supply air temperature at 100 W/m² was same in both systems. In the SWIT, temperature at the occupied zone was same, but temperature at whole large enclosure became higher than the MIX. A part of cooling loads of tooling machines, lamps, and outside wall were transferred into the occupied zone by radiant flux. The SWIT exhaust air temperature was higher due to the indoor load toward ceiling, so that, the SWIT was able to reduce the energy consumption of the chiller.

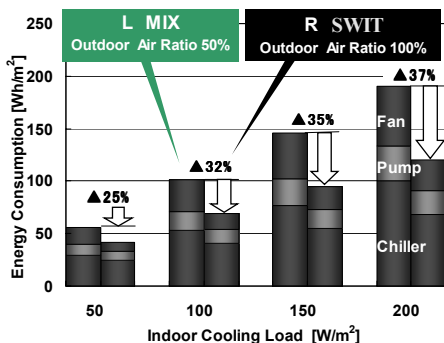


Figure 8. Comparison of Energy Consumption at Cooling Peak Load

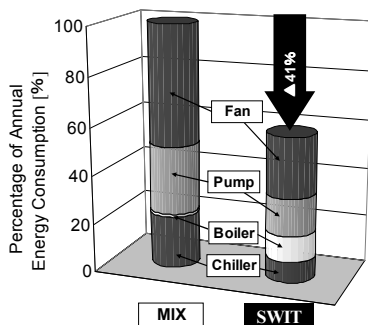


Figure 9. Comparison of Energy Consumption per a Year (Indoor Cooling Load 100 W/m²)

4-3 Annual energy consumption

Figure 9 shows the result comparison on annual energy consumption where the indoor cooling load is 100 W/m^2 . The annual energy consumption was reduced 41% compared with the MIX.

We estimated the monthly energy consumption. The reduction of 43% in energy consumption was achieved compared to the MIX in the summer. In the intermediate season where the outdoor air enthalpy becomes lower, energy conservation was greater than the summer due to the cooling by use of the outdoor air and the energy consumption was ca. 50% of the MIX. In the winter where the outdoor air temperature is low, the SWIT required much more heating than the MIX in the case of warm return air ratio of 50%. However, the SWIT needed little energy to feed the air so that the energy consumption was reduced approximately 32% compared to the MIX. The heating source utilized here was a steam boiler, however when same mass of waste heat from the factory can be utilized then even more energy can be saved. The annual energy consumption estimated in that case will be approximately 50% that of the MIX.

5. CONCLUSIONS

In large enclosure where air conditioning is difficult due to the area and height dimensions, and in particular in factories that support Japan's basic industrial structure, the large quantities of heat generated by the machinery as well as the contaminant load just like oil mist require huge equipment capacity and energy for HVAC systems, so achieving the same level of comfort and efficiency as an ordinary office is extremely difficult. According to these results, we obtained that the SWIT was capable of providing a comfortable and clean air environment over the years on the comparison with the MIX. The SWIT was able to save energy while at the same time reducing the previously required equipment capacity.

All those involved in the research and development of the SWIT will be extremely delighted when it can contribute to improve the quality of the working environment.

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