Numerical Analysis of Ventilation Effectiveness in Occupied Zones for Various Industrial Ventilation Systems

Seohiro Kikuchi [a*], Kazuhide Ito [b], Nobuyuki Kobayashi [c]

[a] Graduate Student, Tokyo Polytechnic University, Japan
[b] Dr. Eng., Assistant Professor, Tokyo Polytechnic University, Japan
[c] Dr. Eng., Professor, Tokyo Polytechnic University, Japan
[*] *E-mail address:* s-kikuchi@kawamoto-ind.co.jp

Abstract

When the generation of pollutants is assumed locally in industrial workspaces, such as factories or industrial plants, there is a legal obligation in Japan to set up local exhaust systems of a food and a push-pull type. The local exhaust systems are effective in controlling the diffusion of pollutants generated in the workspace, and much research has already been done on the performance of these systems. However, there have been virtually no studies on the performance of push flow type ventilation systems for industrial workspaces, which have a local supply inlet and are able to directly dilute and control the direction of the convective flow of the contaminants.

In this paper, CFD (Computational Fluid Dynamics) simulations are carried out in order to confirm the performance of a push flow type local ventilation system for industrial workspaces, which are characterized by a large enclosure with specific pollutants generation in local areas. The Normalized Concentration in the Occupied Zone (*Cn*) which is the ratio of the average contaminant concentration in the occupied zone (*Cp*) to the concentration for completely mixed indoor air (*Ce*) is used to evaluate the effectiveness of local ventilation for industrial workspaces.

1. Introduction

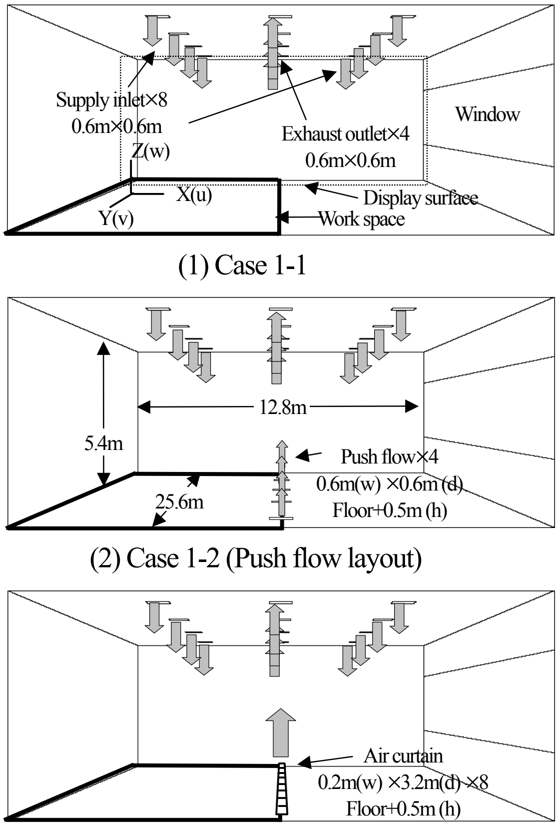
In Japan, the acceptable contaminant concentration level in industrial workspaces is strictly regulated by the Industrial Safety and Health Law. The acceptable concentration level signifies the concentration below which it can be considered that the substance has virtually no harmful effects on workers in the space, even if they are exposed to this level of concentration everyday. It is the same as the ACGIH Threshold Limit Values.

In designing the ventilation for an industrial workspace, e.g. a factory or industrial plants, all engineers follow the regulations on the performance of the ventilation equipment, and design the concentration in the industrial workspace to be less than the acceptable concentration recommended by the Japan Society for Occupational Health. They normally design the ventilation system around local exhaust equipment components such as a canopy, hood, push-pull type ventilation system, and a dust collector or air purification device.

From the viewpoint of controlling the local air quality, it is important to study the performance of, not only the local exhaust ventilation system, but also the local supply inlet system such as push flow type ventilation systems. In this paper, the performance of push flow type ventilation systems and air-curtain systems for controlling the local air quality are discussed for industrial workspaces.

2. Normalized Concentration in the Occupied Zone

The ventilation standard HASS 102 of the Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan (*SHASE* Japan) is the only technical standard on ventilation in Japan. HASS 102

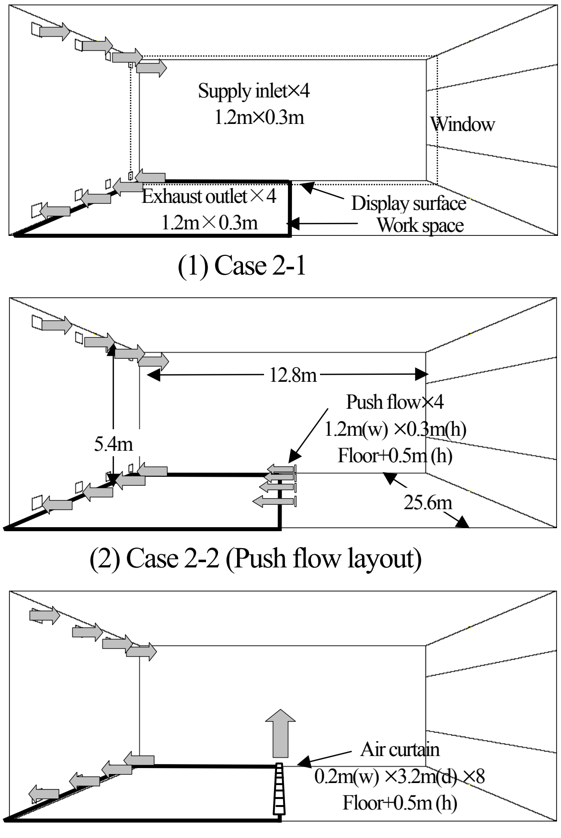


(1) Case 1-1

(2) Case 1-2 (Push flow layout)

(3) Case 1-3 (Air curtain layout)

Fig. 1 Analyzed Model and Ventilation System (Case 1)



(1) Case 2-1

(2) Case 2-2 (Push flow layout)

(3) Case 2-3 (Air curtain layout)

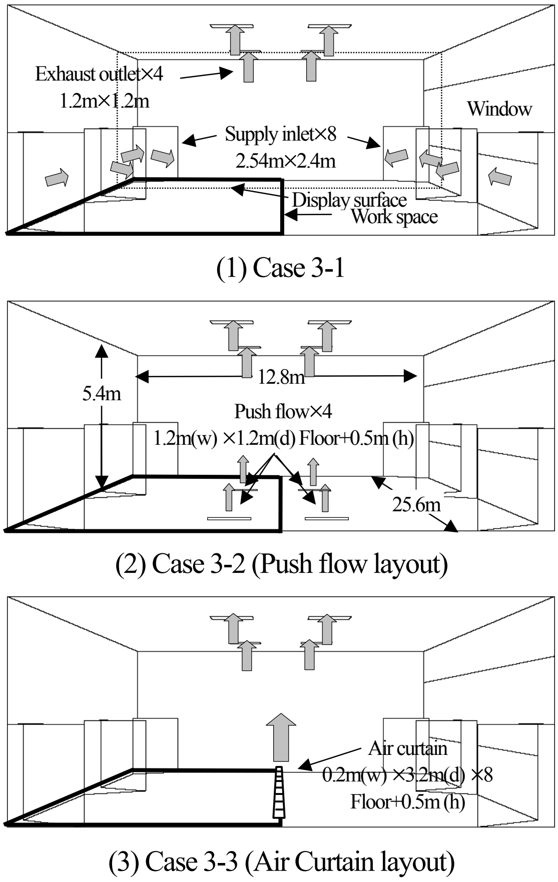
Fig. 2 Analyzed Model and Ventilation System (Case 2)

recommends designing the ventilation by using the "Normalized Concentration in the Occupied Zone (*Cn*)" index of ventilation effectiveness for a general indoor environment. The definition of *Cn* is as follows:

$$C_n = \frac{C_a - C_0}{C_p - C_0} \tag{1}$$

Here, C_a is the average pollutant concentration in the occupied space or target local space [m^3/m^3], C_o is the pollutant concentration of the supplied outdoor air [m^3/m^3], and C_p is the pollutant concentration of the completely mixed indoor air [m^3/m^3]. In this analysis, in order to evaluate the local air quality in an industrial workspace, the *Cn* index is adopted. In this analysis, the occupied zone indicates a space in the workspace and non-workspace respectively where the occupants reside and act (a space 1.8m in height from the floor).

In general, a local exhaust ventilation system is selected for the local ventilation system in order to control and inhibit the diffusion of pollutants in the industrial workspace. For this reason, the index of



(1) Case 3-1

(2) Case 3-2 (Push flow layout)

(3) Case 3-3 (Air Curtain layout)

Fig. 3 Analyzed Model and Ventilation System (Case 3)

Table 1 Air-Conditioning System Conditions

Case	Supply inlet and exhaust outlet layout	U_{in} [m/s]	Re ($\times10^6$)	Push flow	Air curtain
1-1	Supply inlet on ceiling Exhaust outlet on ceiling	0.425	0.16	—	—
1-2		0.425	0.16	○	—
1-3		0.425	0.16	—	○
2-1	Supply inlet on upper wall Exhaust outlet on lower wall	0.855	0.33	—	—
2-2		0.855	0.33	○	—
2-3		0.855	0.33	—	○
3-1	Displacement ventilation	0.025	0.01	—	—
3-2		0.025	0.01	○	—
3-3		0.025	0.01	—	○

Table 2 Push Flow Conditions

Case	1	2	3
Exhaust outlet layout	Ceiling	Lower wall	Ceiling
Velocity of exhaust outlet	0.85m/s	0.855m/s	0.212m/s
Air flow direction	Vertical flow	Horizontal flow	Vertical flow
Layout of push flow outlet	(Refer to Table 1)		
Area of push flow outlet	0.6×0.6 m	1.2m wide ×0.6m high	1.2m×1.2 m
Velocity of push flow	0.5m/s		
Push flow turbulence energy (k_{in})	$k_{in}=3/2(0.5\times0.05)^2$		

Table 3 Air Curtain Conditions

Case	1	2	3
Exhaust outlet layout	Ceiling	Lower wall	Ceiling
Velocity of exhaust outlet	0.85m/s	0.855m/s	0.212m/s
Direction of air curtain	Vertical flow		
Air curtain outlet layout	(Refer to Table 1)		
Area of air curtain	3.2m×0.2m×8m		
Velocity of air curtain	0.5m/s		
Turbulence energy of air curtain (k_{in})	$k_{in}=3/2(0.5\times0.05)^2$		

Table 4 Numerical Conditions

Mesh	Case 1 ; 78(x)×72(y)×35(z)=196,560 Case 2 ; 72(x)×68(y)×51(z)=249,696 Case 3 ; 64(x)×64(y)×27(z)=110,592
Turbulence model	Low Re Type k-ε model
Inflow boundary conditions	U_{in}; show table 1, $k_{in}=3/2(U_{in}\times0.05)^2$, $\varepsilon_{in}=C_\mu\times k_{in}^{3/2}/L_{in}$, $C_\mu=0.09$, L_{in}=1/7 scale of supply inlet
Outflow boundary conditions	U_{out}, k_{out}, ε_{out}=free slip
Wall treatment	No slip
Contaminant	Passive, uniformly and continuously generated throughout half of floor

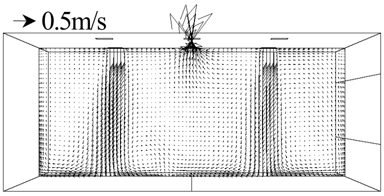
contaminant removal efficiency is used to evaluate the performance of the local exhaust ventilation system. On another front, the *Cn* index can be used to evaluate the concentration level for the whole workspace, and it is useful to control and evaluate the average concentration in a space that has some extension.

3. Outline of the Industrial Workspace Model and Numerical Conditions

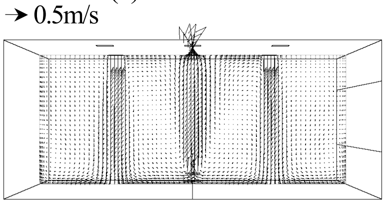
The industrial workspace models analyzed are shown in Figures 1 to 3. The workspace model has dimensions 12.8 (x) × 25.6 (y) × 5.4 (z) m. Three ventilation systems were chosen for the fresh air supply and for the individual ventilation systems in the whole workspace; two local ventilation systems – push flow type and air-curtain type – were set in the industrial workspace model. The industrial workspace model is assumed to consist of two areas: an industrial workspace with a source of contaminants, and a non-workspace area where workers reside. The air quality control was examined in the workspace and the non-workspace with a push flow type ventilation system and the air-curtain system set up in the center of the space.

The boundary conditions of the ventilation system in the whole workspace are given in Table 1. The air change rate of the fresh air was set at 2.5 times/h in all cases from the condition for Min. OA. The local ventilation system conditions for the push flow type and air-curtain type are shown in Tables 2 and 3. A push fan works in the direction of the exhaust outlet for the whole ventilation system, and the air curtain is positioned to divide the workspace from the non-workspace. The push flow and air curtain system are intended to set a convective flow, and no fresh air is introduced.

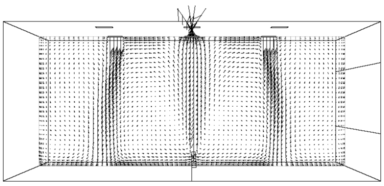
Numerical conditions for the CFD simulation are shown in Table 4. CFD simulations are carried out in the half space of the industrial workspace model to preserve the symmetry in the Y direction. A low Re type k-ε model (Abe-Nagano model) was used as the turbulence model and the QUICK scheme was used for the convection term. In this analysis, to examine the effect of the local ventilation systems under basic conditions, isothermal conditions were assumed.



(1) Case 1-1

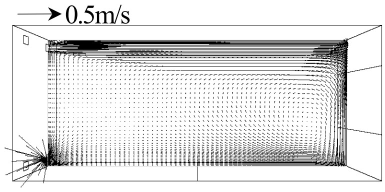


(2) Case 1-2

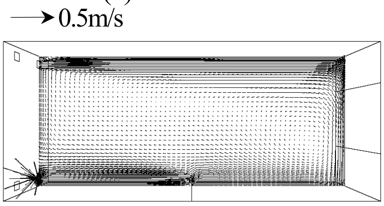


(3) Case 1-3

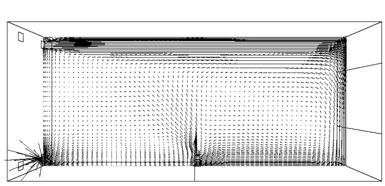
Fig. 4 Flow field in Case 1



(1) Case 2-1

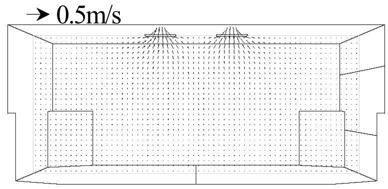


(2) Case 2-2

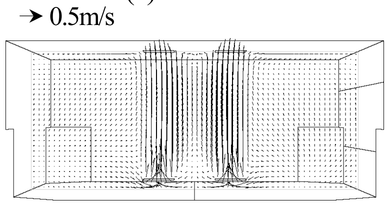


(3) Case 2-3

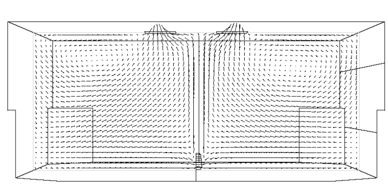
Fig. 5 Flow field in Case 2



(1) Case 3-1



(2) Case 3-2



(3) Case 3-3

Fig. 6 Flow field in Case 3

The contaminant concentration distributions were analyzed by using prior prediction results for the flow fields. It was assumed that the contaminants were generated uniformly and continuously throughout the floor level of the workspace, and moved passively. No pollutants are generated in the non-workspace and the supply air is completely fresh (it does not contain pollutants).

4. Results of Flow Fields

The flow fields predicted by CFD simulation are shown in Figures 4 to 6.

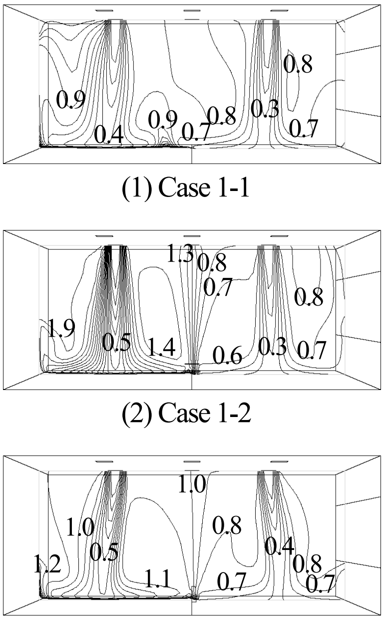
In Case 1-1, which incorporates only a ventilation system for the whole space, a potential flow is formed and no clear convective flow can be observed around the exhaust outlet as shown in Figure 4(1). In Cases 1-2 and 1-3, in which a local ventilation system is installed in addition to the whole ventilation system, the convective flow facing the exhaust outlet is formed by a forced push flow or air-curtain as shown in Figures 4(2) and (3).

In Case 2-1, which has a ventilation system for the whole space, a large circulating flow field is formed along the wall as shown in Figure 5(1). In Case 1-2, which has a push flow type local ventilation system installed, the convective flow facing the exhaust outlet is formed by a forced push flow. In Case 1-3, a circulating flow is obstructed by setting an air-curtain type local ventilation system as shown in Figure 5(3).

In Case 3-1, which incorporates a displacement ventilation system for the whole space, no clear convective flow field can be observed for the entire space as shown in Figure 6(1). In Cases 3-2 and 3-3, in which a local ventilation system is installed, the convective flow facing the exhaust outlet is formed by forced push flow or an air-curtain as shown in Figures 6(2) and (3).

5. Results of Contaminant Diffusion Fields

The contaminant diffusion fields predicted by CFD simulation are shown in Figures 7 to 9. The

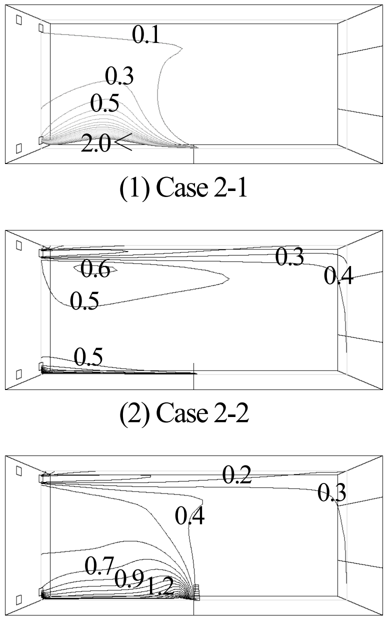


(1) Case 1-1

(2) Case 1-2

(3) Case 1-3

Fig. 7 Con. Distribution in Case 1

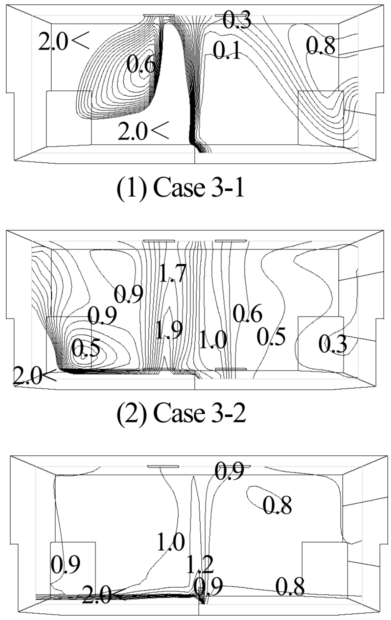


(1) Case 2-1

(2) Case 2-2

(3) Case 2-3

Fig. 8 Con. Distribution in Case 2



(1) Case 3-1

(2) Case 3-2

(3) Case 3-3

Fig. 9 Con. Distribution in Case 3

contaminant sources are set on the floor in the workspace (the non-workspace is excluded). The concentration values are normalized to the completely mixed concentration and they are dimensionless.

In Case 1-1, pollutants generated from the floor in the workspace are uniformly distributed except for the region of influence of the supply air jet as shown in Figure 7(1). In Cases 1-2 and 1-3, in which a local ventilation system is installed, the concentration distribution is divided into two parts; workspace and non-workspace, and the averaged concentration is ascendant in the workspace. On the other hand it is descendant in the non-workspace as shown in Figures 7(2) and (3).

In Case 2-1, pollutants generated from the floor in the workspace are transported directly to the exhaust outlet, and this keeps pollutant diffusion down. In this case, large circulating flow fields are formed along the walls, and the pollutants generated on the floor are exhausted efficiently from the exhaust outlet set up at floor level. In Cases 2-2 and 2-3, pollutants are widely distributed by the forced push-flow, which obstructs the circulating flow along the walls, as shown in Figs. 8(2) and (3).

In Case 3-1, the averaged concentration value in the workspace exceeds 2.0 as shown in Figure 8(1). In Cases 3-2 and 3-3, pollutants are widely distributed by the forced push flow.

6. Results of Normalized Concentration in the Occupied Zone (*Cn*)

Figure 10 and Table 5 show the result for the Normalized Concentration in the Occupied Zone C_n for each case. In Case 1, *Cn* for the workspace is lowest for the whole ventilation system. When adopting a push flow type ventilation system, although *Cn* for the workspace became high, *Cn* for the non-workspace became low. When adopting an air-curtain system, the tendency of *Cn* was similar to the case of the push flow type ventilation system.

In Case 2, *Cn* for the workspace and non-workspace became worse for both a push flow type ventilation system and an air-curtain system. When the ventilation system in the whole space worked well to control the air quality in the local area, the installation of a local ventilation system seemed to be a factor in degrading the air quality.

In Case 3, *Cn* for the non-workspace was low, although *Cn* for the workspace was an extremely

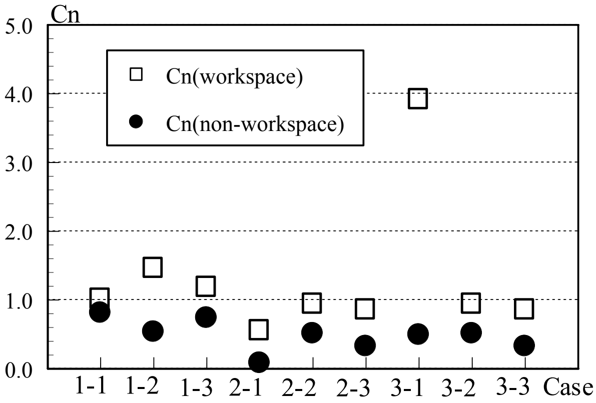


Fig.10 Results of *Cn*

Table 5 *Cn* for each case

CASE	workspace	non-workspace
Case 1-1	1.01	0.81
Case 1-2 (push)	1.46	0.53
Case 1-3 (air-c)	1.18	0.74
Case 2-1	0.55	0.08
Case 2-2 (push)	0.94	0.51
Case 2-3 (air-c)	0.85	0.32
Case 3-1	3.91	0.49
Case 3-2 (push)	0.94	0.51
Case 3-3 (air-c)	0.85	0.32

high value for the whole ventilation system. *Cn* for the workspace and non-workspace became low with the installation of both a push flow type ventilation system and an air-curtain system.

In this analysis, except for Case 3 which adopts a displacement ventilation system for the whole space, the installation of a push flow type ventilation system did not work well to control the air quality. Contaminant diffusion fields came close to perfect mixing concentrations because of the interflow or mixing by the forced push flow. Use of a push flow type local ventilation system becomes effective under conditions of a tranquil flow field.

It was very different neither push flow type local ventilation system nor air-curtain type in respect of the air quality control of non-workspace.

7. Concluding Remarks

(1) Flow fields and contaminant concentration distributions are analyzed using CFD for three different ventilation systems in the whole workspace and with two types of local ventilation systems.
(2) In this analysis, *Cn* in the non-workspace became 1.0 or less in all cases.
(3) The installation of a push flow type ventilation system did not work well in controlling the local air quality except for the case in which a displacement ventilation system was adopted for the whole space.
(4) Installing a push flow type local ventilation system with a tranquil flow field shows the potential to work efficiently.

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