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The Effect of Ventilation Types on Pollutant Removal in a Large Space Plant with Multiple Pollutant Sources

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Key Words

Large space · Multiple pollutant sources · CFD · General displacement · Local exhaust

Abstract

This study numerically investigated the influences of ventilation designs on pollutant removal in a large space with multiple pollutant sources. The types of ventilation include general displacement and local exhaust ventilation with either partitioned or non-partitioned working field. The study demonstrated that the outlet positions and outlet flow rate distribution for local exhaust ventilation are more important than those of the general displacement type. It would be more effective to design local exhaust by placing the outlets on the midstream and downstream of the machines rather than on all the machines. The results also demonstrated that the effect of local exhaust type would not be more superior to the general displacement type due to the large space in plant and multiple pollutant sources such as oil gas pollutant source, mist of metalworking fluid, etc.

Nomenclature

A = Area of pollutant source (m^2)
C = Concentration of pollutant
In1 = Outdoor air inlet for lower working region
In2 = Outdoor air inlet for upper working region
QI = The ratio of inflow rate of In1 to total inflow rate, dimensionless
QO = The ratio of exhaust rate of Out1 to total exhaust rate, dimensionless
Out1 = Outlet for lower working region (for local exhaust cases, it means all local exhausts in lower working region)

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Out2 = Outlet for upper working region (for local exhaust cases, it means all local exhausts in upper working region)

V = Plant space (m^3)

Introduction

In the recent years, preserving the quality of high-tech products have become an imperative issue due to the environmental concerns and demand of consumers for "clean" and "green" products. Therefore, different processes that would engender various kinds of clean rooms would lead to a better long-term performance of the high-tech products. In general plant, pollutants generated by certain pollutant sources may be of concern to those who work in the plant. Therefore, ventilation is an important consideration for any indoor and built environment like industrial plants. There are several kinds of pollution that could be generated from an industrial plant, for example, the mist of metalworking fluid (MWF) in mechanical factories. Sheehan et al. [1] mentioned that inhalation of MWF mist may cause irritation of the lungs, throat and nose. Constant exposure to MWFs may incur asthma and lead to prompt decline of lung function, resulting in irreversible damage of heart or lung function [1]. MWF particles less than 2.5 μm in diameter will enter into the deepest part of the lungs, consequently endangering the non-ciliated alveoli and causing greater risk to human health than larger particles [2]. Adler et al. [2] proposed two different mechanisms, namely atomisation and vaporisation/condensation, as the sources for cutting fluid mist. Sheehan et al. [1] also depicted one way to prevent employee from exposure to MWF via installing an exhaust ventilation system to prevent the accumulation or recirculation of airborne contaminants in the workplace. In summary, these kinds of pollution can pose a great threat to workers, and must be controlled whenever possible.

There have been numerical investigations to determine effectiveness of ventilation and airflow patterns in clean rooms in hospitals and in other buildings. Loomans et al. [3] described the development of a performance assessment methodology for the assessment of the efficiency of a ventilation system in an operating theatre. Wang et al. [4] investigated the effects of various parameters on different occupational states in a newly constructed cleanroom by field-testing and computer simulation. Li and Zhu [5] introduced "response coefficient to supply air" and "response coefficient to contaminant source" to characterise spatial and temporal distribution under different air distribution patterns. Tian et al. [6] investigated particle dispersion in a room under stratum ventilation and under displacement ventilation from numerical simulation. Calogine et al. [7] simulated the transport of carbon dioxide in buildings using two software tools. Zhou and Kim [8] numerically investigated the indoor environmental conditions through the calculated velocity field, temperature field and CO_2 concentration distribution during cooking in a kitchen in a typical Korean apartment. This study concerns with effectiveness of ventilation and airflow in a large industrial metal processing plant. The best way to reduce the pollution gases is to lower their concentrations via filtration and ventilation. However, Hama [9] pointed out that ventilation may overkill reduction of pollution, and was not the only way to control contaminants of industrial process and nuisance by-products safely. Thiel [10] discussed methods that would re-process non-toxic contaminants released in the manufacturing areas by purifying the air. This would allow the air to be safely recycled within the building and also minimising the fuel and power usage. Goldfield [11] showed that local exhaust ventilation was more effective than general ventilation in the vicinity of contaminant sources; requiring approximately one-third of the general ventilation flow rate to effect the same reduction of contaminant concentration. Heinsohn et al. [12] described a computational procedure to predict contaminant concentrations at arbitrary locations in the vicinity of open vessels containing volatile liquids. Godish et al. [13] conducted a parametric study to examine the performance of ventilation system by measuring the levels of metabolically augmented CO_2. Goodfellow and Berry [14] indicated that dust and fume emissions could be minimised by planning the design process carefully. By selecting the adequate and appropriate ventilation system, the influence of CO_2 pollution can be eliminated. Forster and Burgess [15] developed a technique to test the influences of gas cabinets, optimum geometry and exhaust rate on the ventilation performance. Palau and Setton [16] showed that supplementary ventilation systems can successfully prevent the spread of airborne contamination into the plant areas. Pfeifferand and Brunk [17] pointed out the inappropriateness of supplying air in the welding halls. With a design of supply air from the hall floor area, the air distribution from floor to ceiling can be significantly improved. Breum and Skotte [18] used a multipoint, single tracer gas (SF_6) measuring unit to determine displacement airflow within a large workshop. They found that the displacement air flow could create two different flow regions. The heat and air pollutants accumulated in an upper region would be acceptable as working conditions in the occupied zone. Curd [19] considered the influence of the free jet airflow and the wall jet airflow on the overall performance in removing the containments from an industrial working space. Saamanen et al. [20] evaluated the performance of a horizontal displacement ventilation system in two lamination rooms where reinforced plastic boats up to 17 m in length are manufactured. The tracer gas pulse technique was used to measure the air exchange efficiency, local air exchange index and the effectiveness of contaminant removal. Pannkoke [21] conducted a parametric study to identify the effects of the building code in relation to the industrial plant air pollutants, and the building heat loss/gain in respect to the safety and performance of HVAC systems within industrial facilities. Gill and Patterson [22] investigated the design and installation of a 3600-ton central plant, which have an air capacity of 750,000 cfm in a manufacturing facility that was originally cooled by numerous split-system units. Minichiello [23] described general ventilation plants with variable outdoor airflow rates that were subjected to various ambient conditions. Deaves et al. [24] used a simple zone modelling, based on the equilibrium assumption of vapour and air, to calculate the rate of release of a dense vapour from a building. Hayashi et al. [25] used computational fluid dynamics (CFD) analysis to examine the characteristics of contaminated indoor air ventilation in a human occupant room. A simplified two-dimensional model was applied in their study. Chao and Wan [26] experimentally investigated the ventilation performance and pollutant distribution in traditional ceiling type, top-return type and floor-return type ventilation systems. Tracer gas was used to determine air leakage and removal effectiveness of smoke pollutant being dispersed in the room. Hunt and Kaye [27] examined the time taken to flush pollutants from a naturally ventilated room. A simple theoretical model was developed to predict the time taken for neutrally buoyant pollutants to be removed from a room. Bolster and Linden [28] studied the transport of an initially uniformly distributed passive contaminant in a displacement-ventilated space. Analytical and numerical models were developed to compare the average efficiency of contaminant removal between traditional mixing and modern low-energy systems. Wan and Chao [29] investigated the transport characteristics of droplet nuclei in different ventilation modes using a validated multiphase numerical model. The study found that the unidirectional-upward system was suitable for removal of small droplet while single-side floor system was effective for large droplet. Wang and Chen [30] applied a coupled multizone-CFD model to calculate airflow and contaminant dispersion in a three-storey, naturally ventilated building with a large atrium, assuming that a contaminant was released in the atrium.

The pollution source in the foregoing researches was from a single source or from a constricted small area of an industrial building. In a large industrial plant, widespread pollutants could be generated by multiple sources to give rise to different situations as compared to the preceding studies described. Hence, it would be valuable to explore the influence based on association of various multi-pollution sources. This study investigated the dispersion of multiple oil gas pollutant sources generated during a typical metal machining process within a mechanical machining plant. A numerical computation is applied to simulate the effect of different ventilation designs on dispersion of pollutant concentrations. Types of ventilation considered, included the general displacement type and local exhaust one, with and without the influence of the partitioned upper and lower working regions.

Physical Model

The physical model of this study is based on a mechanical machining plant having a corresponding length, width and height of 60, 24 and 9 m, respectively. A part of the space is divided into an office space with the length, width and height of 60, 12 and 6 m, respectively. The machine centres that occupied a volume of $3 \times 2.4 \times 2.25\,\text{m}^3$ are uniformly distributed within the plant. A total of 28 machine centres consisting of seven rows by 4 columns as outlined from Figure 1(a). The working region is further divided into three zones (I, II and III) in order to compare their pollutant concentration as shown in Figure 1(b). The partition between upper and lower working regions is shown in Figure 1(c).

The assumptions for simulation of this study include:

1. Generally, the heat generated in the machining process is mostly absorbed by oil coolant. The oil coolant is cooled by a cooling device and removes the heat to outdoors, and very little residual heat would remain indoors. Due to a high outdoor air flow rate, a uniform temperature would prevail in the outdoors and in the plant, indicating a negligible influence of forced and natural convections.

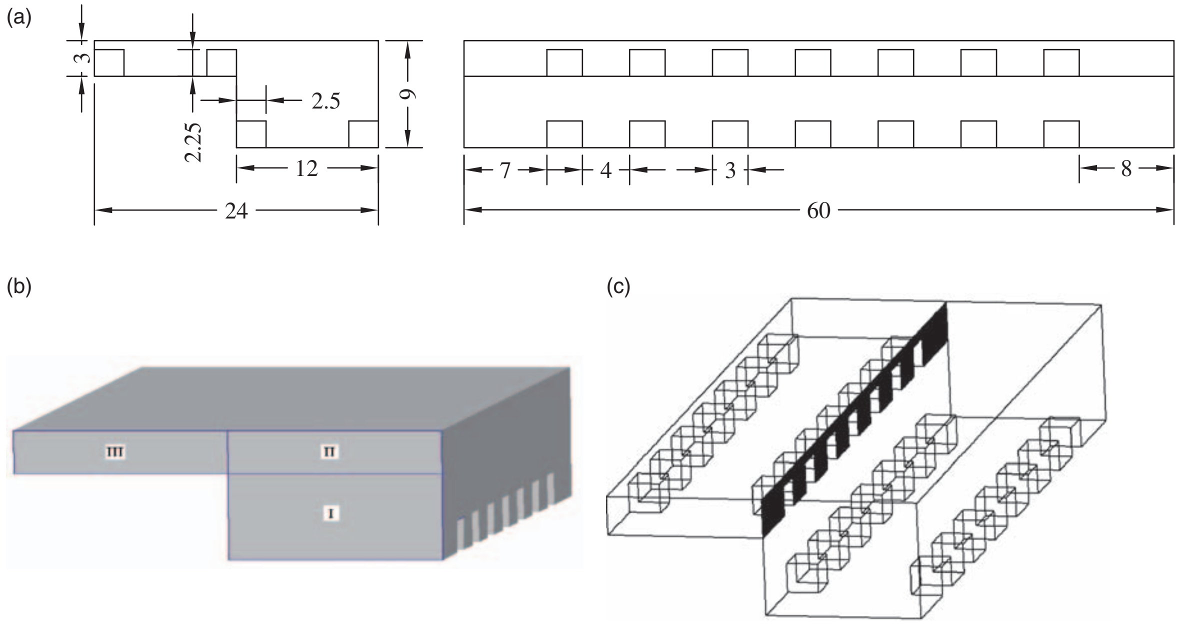


Fig. 1. The configuration of the mechanical plant: (a) geometry, unit: metre; (b) three zones of this plant; (c) the working regions with partition.

2. There are two working fluids in this study. One is air (density: 1.18 kg·m^{-3}, dynamic viscosity: 1.81×10^{-5} N·s·m^{-2}) and the other is the mixture of air and oil gas generated from the machining centres. Oil gas is well mixed with air before it is diffuse into the plant. The pollutant is made of 10% of lubrication oil gas and 90% of air. The density of this pollutant gas mixture is 3 kg·m^{-3} while the viscosity is assumed to be the same as air.
3. The effects of workers and other objects in the plant are negligible.
4. The flow is incompressible. The physical properties of air and pollution are constant.

The boundary conditions are shown in Figure 2 and are described by the following:

1. The regions where outdoor air flows into the plant are set as inlet boundary condition. A uniform velocity is given at each inlet. The velocities are calculated by the flow rates at inlets. On these boundaries, fresh air concentration fraction is designated as 1(100% fresh air) while pollutant concentration fraction is regarded as 0 (no pollutant).
2. The regions where pollutants enter into the plant are also set as the inlet boundary conditions. A uniform velocity is given at each inlet. The velocity is determined by the pollutant's generation rate. On these boundaries, fresh air concentration fraction is designated as 0 (no fresh air) while pollutant concentration fraction is 1 (100% pollutant).
3. The regions where all of the gases (air, pollutant or their mixture) leave the plant are set as the outlet boundary conditions. The concentrations of all gases in these regions are calculated by simulation programme.
4. All the solid walls are set as wall boundary conditions. The velocity near the wall is determined by "wall function".

The subsequent simulations are made with the pollutant generation rate being fixed at 0.1 m^3·s^{-1} per machine and so the total generation from all the machines is 2.8 m^3·s^{-1}.

Solution Methodology

The finite-volume based software STAR-CD commercial package was used for the simulation. By considering the plant's huge size and its considerable large characteristic length, the high Reynolds number k–ε turbulent model was adopted towards the momentum and species equations. The convection terms in momentum and species equations were discretised by upwind difference method; noting that the flow field would be very complicated due to the presence of recirculating flows. The upwind difference method was highly numerically

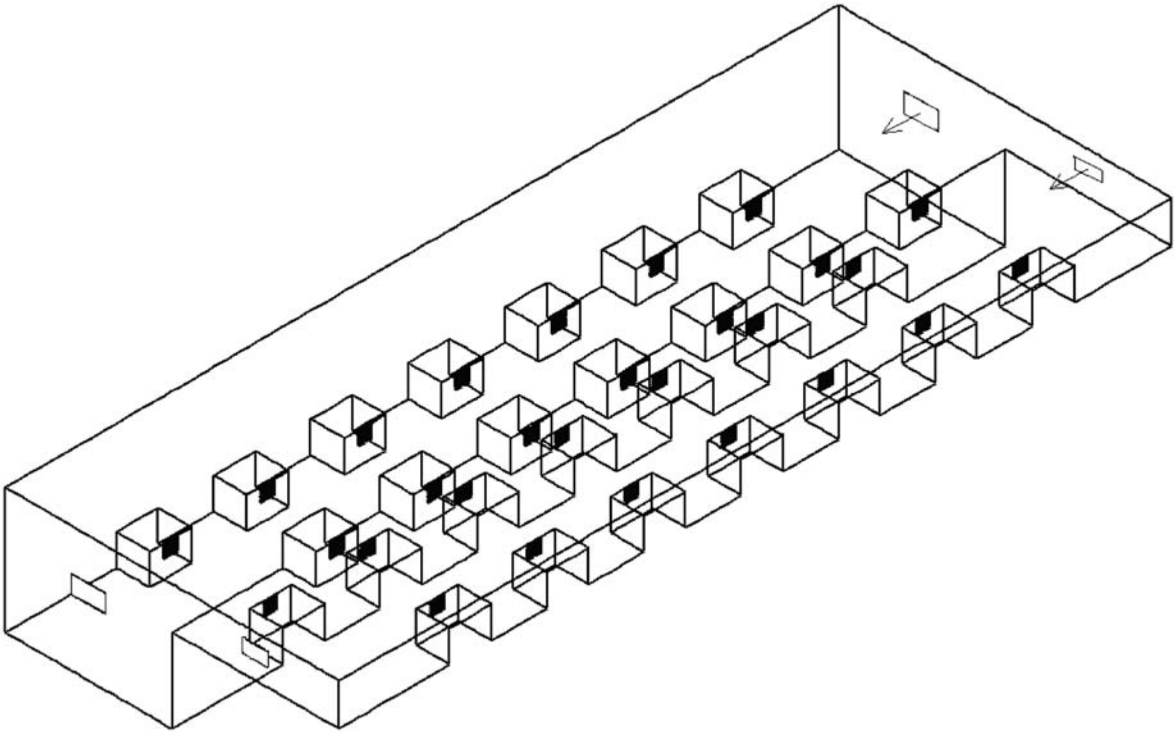


Fig. 2. The inlets, outlets and pollution sources.
Note: (■) represents the pollution sources.

stable but it has a disadvantage of low accuracy. The accuracy problem of upwind method could be overcome using more grids. The iterative procedure was performed using PISO (PISO, Pressure Implicit with Splitting of Operators, [31]) scheme. There were extra prediction-correction steps in PISO scheme and more computational time was needed. The benefit for employing the PISO method was due to its effectiveness to achieve the convergence of the pressure field. The convergent criteria were: the residuals of velocities, pressure and turbulent kinetic energy that were less than 5×10^{-5}.

A grid system would be structured; small and fine meshes were applied onto the walls, inlets and outlets, while large and coarse meshes were applied on the other regions.

The average pollutant concentration is defined by Equations (1) and (2):

$$\text{Total average pollutant concentration} = \sum (C_i \times V_i)/Vt, \quad i = 1 \text{ to } n \tag{1}$$

$$\text{Zone average pollutant concentration} = \sum (C_i \times V_i)/V_j, \quad i = 1 \text{ to } nj, j = 1,2,3 \tag{2}$$

where C_i is the pollutant concentration of the ith cell; V_i the volume of the ith cell; V_t the total volume of plant; V_j the volume of the jth zone; n the number of total meshes; nj the mesh number of the jth zone.

The mesh numbers for the grid test were: 153,344, 301,344, 436,576 and 598,766.

The convergent criterion used was the same as aforementioned. The total average pollutant concentrations in different mesh numbers were compared and as shown in Table 1. The relative deviation between 450,000 and 600,000 mesh numbers was about 0.5%. In order to have a shorter computational time, about 450,000 meshes were used in the numerical computation of this study.

Results and Discussion

Validation of STAR-CD package used in this study is as shown in Figure 3. Chung and Hsu [32] published their work about the effect of flow field concerning the ventilation efficiency of containment. Both the experimental and numerical investigations were included in their study. In order to validate the package, the work of Chung and Hsu was numerically reiterated and a thorough comparison of their experimental results was made. The turbulent model and numerical scheme used for this validation were the same as aforementioned. The detailed

Table 1. The results of numerical experiment

Mesh number	153,344		301,344		436,576		598,766
Total average concentration	0.2939		0.2890		0.2862		0.2847
Relative error (%)		1.71		0.966		0.527	

6 ACH, QI = 0.75, QO = 0.75, $A = 3\,\mathrm{m}^2$ pollution generation rate $0.1\,\mathrm{m}^3{\cdot}\mathrm{s}^{-1}$.

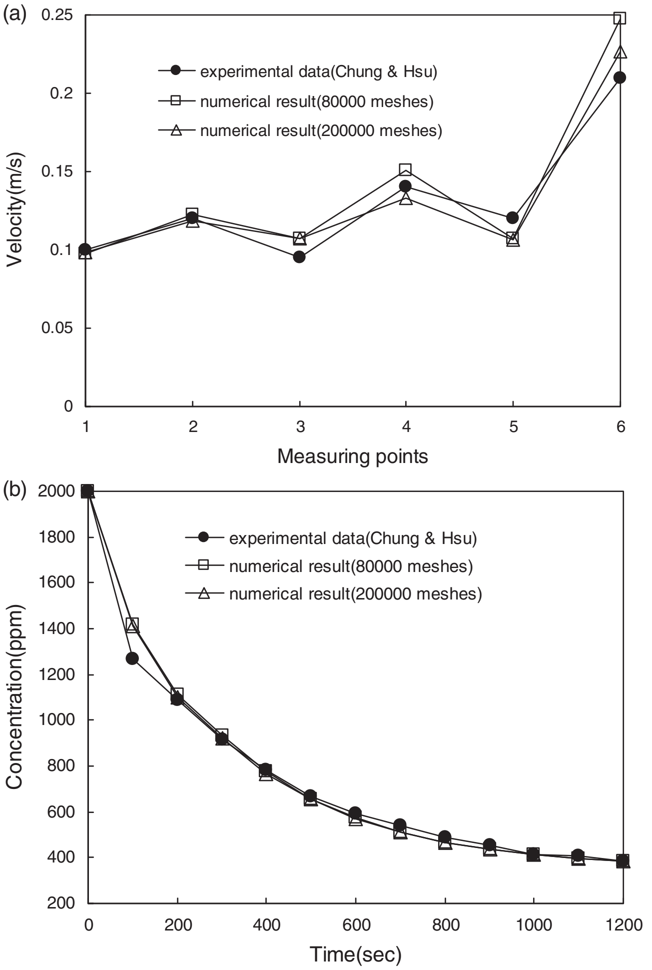


Fig. 3. Numerical results compare with the existing experimental results: (a) local velocities, (b) outlet concentration.

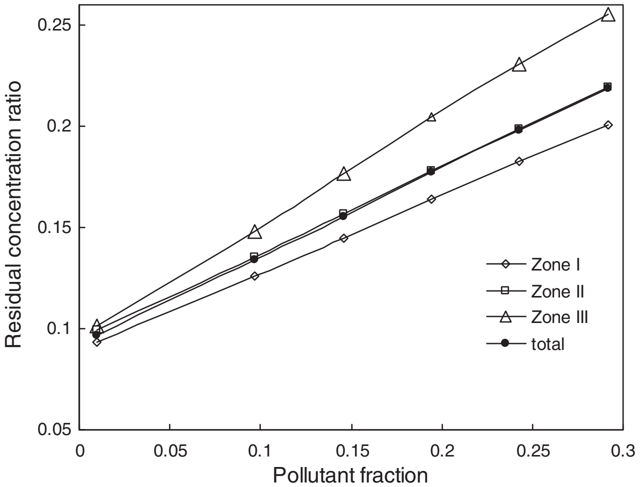


Fig. 4. The effects of air change rate on the pollution concentration when $A = 1\,\mathrm{m}^2$, QI = 0.75 and QO = 0.75.

geometry and boundary conditions have been described [32]. As shown in Figure 3(a), the computed velocities agreed well with the measurements. Besides, the deviations between the computational and experimental velocities would decrease as the mesh number increases. The concentration decay was also consistent with the computed results as shown in Figure 3(b). In summary, the program package was capable of handling this type of problems with accuracy.

General Displacement Ventilation

The effect of pollutant fraction on pollutant removal is shown in Figure 4. The pollutant fraction is defined as the ratio of pollutant generation rate to the fresh air flow rate. The "residual concentration ratio" shown in Figure 4 is the concentrations obtained from Equation (1) or (2) normalised by the concentration of pollutant sources. QI is the ratio of inflow rate of In1 to total inflow rate and QO is the ratio of exhaust rate of Out1 to total exhaust rate. The "residual concentration ratio", QI and QO are all dimensionless in all the figures of this study. A very small pollutant fraction would mean that the fresh air flow rate was much higher than the pollutant generation rate. Figure 4 shows that the total and the average pollutant concentrations within the zones shared a linear relationship with the pollutant fraction. A high air change rate would effectively dilute the pollutant concentration. However, when the pollutant fraction was 0 and the residual concentration was about 0.093, an increase in the ventilation rate alone would not be sufficient to eliminate the pollution completely. This was because with a very high ventilation rate, most of the fresh air would pass through without carrying any pollution with it.

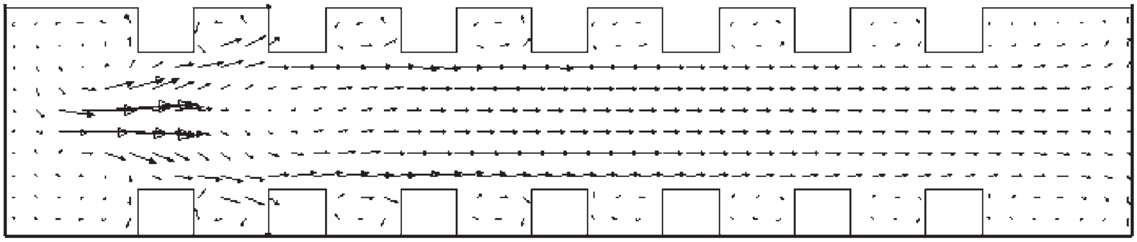


Fig. 5. The velocity vector diagram on the cross-section $y = 1.75\,\mathrm{m}$ for 6 ACH, $A = 1\,\mathrm{m}^2$, $QI = 0.75$ and $QO = 0.75$.

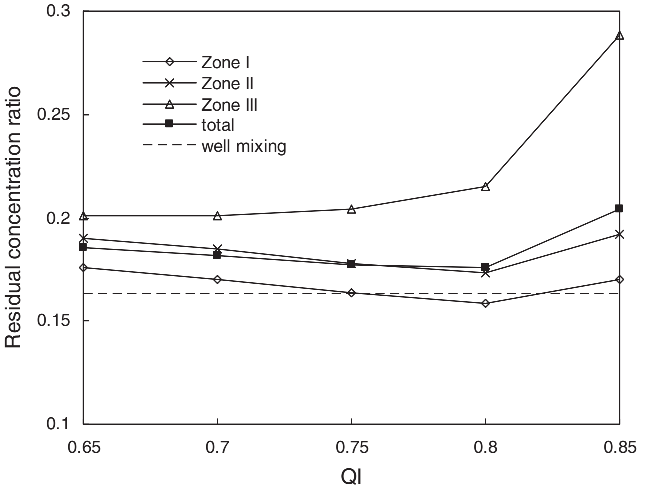


Fig. 6. In a fixed total ventilation rate, the effect of flow rate distribution to each inlet on the pollution concentration.
Note: $A = 1\,\mathrm{m}^2$, $QO = 0.75$ and 6 ACH.

Figure 5 shows a schematic diagram of the circulating air flows between the machines, showing that the pollutants between two machines would be hard to entrain into the main air flow, however high the fresh air flow rate.

Figure 6 shows the effects of QI on pollutant removal for a given total fresh air flow rate. A straight dashed line in Figure 6 represents the well-mixing condition, as defined by Equation (3):

$$\text{Well} - \text{mixing concentration} = \text{pollutant generation rate}/(\text{pollutant generation rate} + \text{total fresh air flow rate}) \quad (3)$$

With a total pollutant generation rate of $2.8\,\mathrm{m}^3 \cdot \mathrm{s}^{-1}$ and a fresh air flow rate of $14.4\,\mathrm{m}^3 \cdot \mathrm{s}^{-1}$ (6 ACH), the corresponding well-mixing residual concentration was 0.1628. The well-mixed concentration would be an average concentration when the pollutant generated in the plant was perfectly mixed with the outdoor fresh air. This value can be used to examine the effect of pollutant removal. When the total average pollutant concentration exceeds the threshold value, this would lead to part of the fresh air leaving the plant before mixing with the pollutant.

QI in Figure 6 is the ratio of flow rate of In1 to the total inflow rate. In Figure 6, there was a local minimum pollutant concentration occurring at $QI = 0.8$, a further increase of QI would lead to a considerable increase in the pollutant concentration. The highest value was found at $QI = 0.85$. Note that when $QI = 0.85$ this would mean that only 15% of the total flow rate was from In2. Therefore, the flow velocity in Region III was too low to create a continuous flow stream. Hence, the pollutant in the upper working region could not be effectively removed thus causing zone III to become highly contaminated. The high concentration of pollutant in zone III would diffuse into zones II and I and subsequently would increase the pollutant concentrations within these two regions. In1 was used to remove the pollutant in zones I and II and would require a higher flow rate than those in In2. However, when the flow rate of In1 was too high, an opposite effect in pollutant removal could happen. Although the total average pollutant concentration of $QI = 0.8$ was slightly lower than that of $QI = 0.75$, the pollutant concentration of zone III of $QI = 0.8$ exceeding that of $QI = 0.75$.

In a practical design, one should consider the individual pollutant concentration in each of these three regions rather than on the total average pollutant concentration alone. The $QI = 0.75$ would be better than $QI = 0.8$ despite its total average pollutant concentration was slightly higher. Since the outlets of general displacement ventilation were located far from the pollutant sources, the pollutant cannot be directly removed from outlets. Thus, the well-mixing concentration could be the limit of the general displacement ventilation.

Figure 7 shows the effects of QO on the pollutant removal with a fixed total ventilation rate. QO is the ratio of flow rate of Out1 to the total flow rate. It appears that the influence of QO on pollutant removal was negligible; this was applicable in either the individual zone pollutant concentration or in the total average pollutant concentration. The reason of the negligible influence of QO was due to the considerably long flow path which had afforded enough space and time to allow the fresh air to mix with the pollutant. Therefore, adjacent to the outlets, a homogeneous (not perfectly homogeneous) flow field would prevail. The results have demonstrated that the effect of flow rates of the two outlets could have a very small effect on pollution concentration. The effect of outlet positions showed similar results.

A different arrangement was schematically shown in Figure 8. The diagram shows some different inlet positions; these are listed in Table 2.

The simulations were conducted by systematically changing the locations of inlets. Figure 9 shows the effect of different locations of In1 and In2 on the pollutant concentration for cases IG0–IG7, showing the variation in the total average pollutant concentration was kept relatively unchanged while the concentrations with the zone revealed significant variations. This was particularly true for IG0–IG3. The results illustrated the importance of considering the inlet position of the airflow for the design of a general ventilation system.

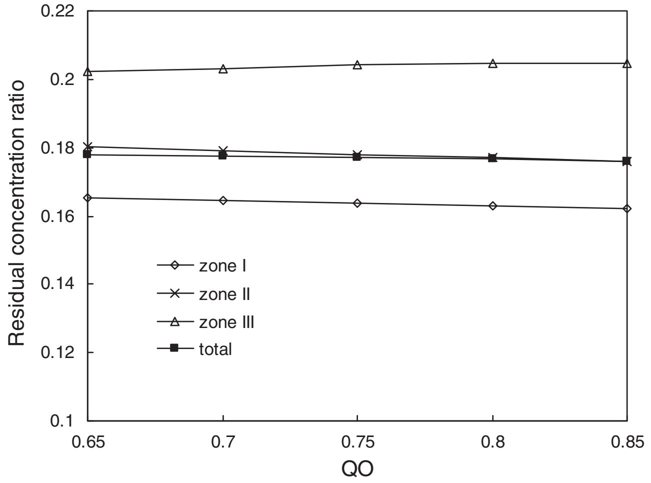


Fig. 7. In a fixed total ventilation rate, the effect of flow rate distribution to each outlet on the pollution concentration.
Note: $A = 1\,\text{m}^2$, QI = 0.75 and 6 ACH.

Figure 10 shows the comparison of the average concentration between working regions with and without partition subject to the influence of QI. The total average pollutant concentration of working region with partition is generally lower than those without partition. As shown in the figure, the effect of QI on working region with partition seems weaker than that without partition. The pollutant concentration of zone III was shown to be very high in working region with partition, especially at a large QI. When the upper and lower working regions were partitioned, only one inlet and one outlet were used to remove the pollutant generated in each working region. For QI = 0.8, the flow rate of In2 was too small, to cause a rapid rise in the pollutant concentration within zone III. In the other side, the fresh air to zones I and II was sufficient at a high QI. Nevertheless, further increase in air flow rate could not ensure effective pollutant removal in zones I and II. For QI = 0.8, part of pollutant in zone III would diffuse out to zone II and would be removed from Out1 in the working region without partition. This would make the pollutant concentration of zone III in the working region without partition to be lower than those with partition.

The role of zone II was to act as a buffer for zone I when the working region was partitioned and for zones I and III when the working region was not partitioned. The pollutant should be carried away by the ventilation stream; otherwise, it will diffuse to working zone and

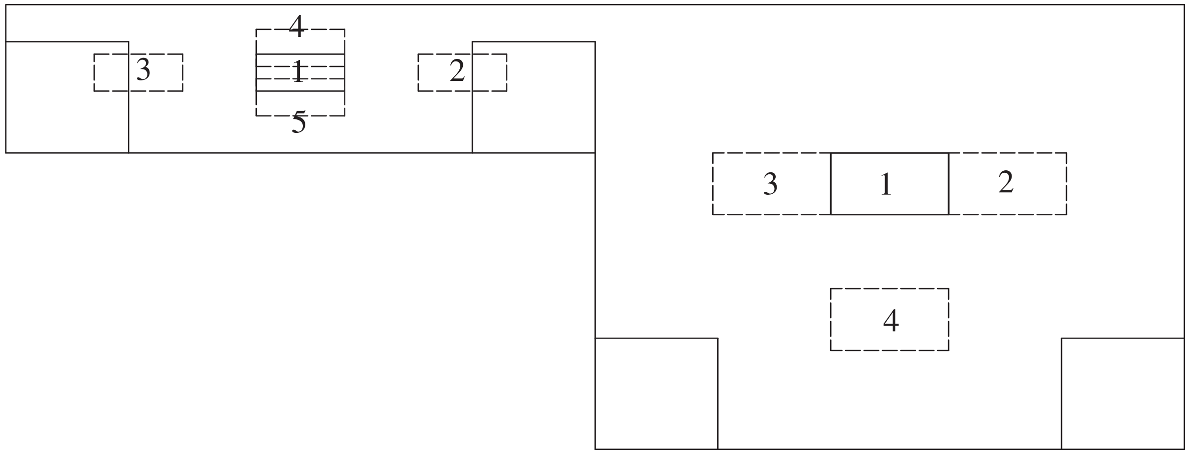


Fig. 8. The locations of inlets for different designs.

Table 2. The inlet positions in general displacement ventilation

Case	IG0		IG1		IG2		IG3		IG4		IG5		IG6		IG7	
Inlet	In1	In2	In1	In2	In1	In2	In1	In2	In1	In2	In1	In2	In1	In2	In1	In2
Position number	1	1	1	2	1	3	3	1	2	1	2	5	2	4	4	1

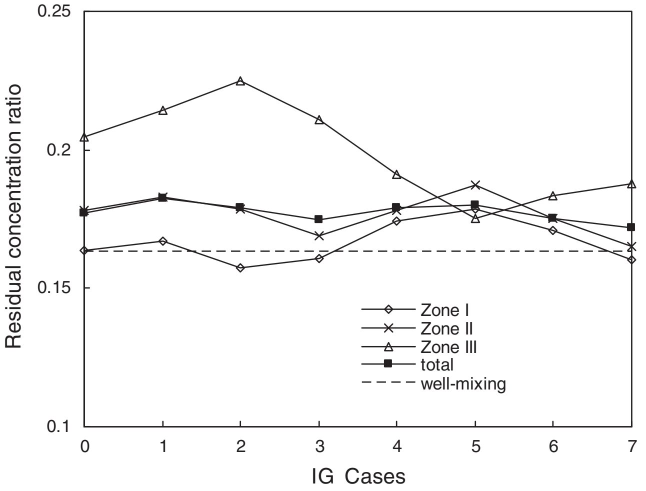


Fig. 9. In the general displacement ventilation, the effect of inlet locations on the pollution concentration.
Note: $A = 1\,\mathrm{m}^2$, QI = 0.75, QO = 0.75 and 6 ACH.

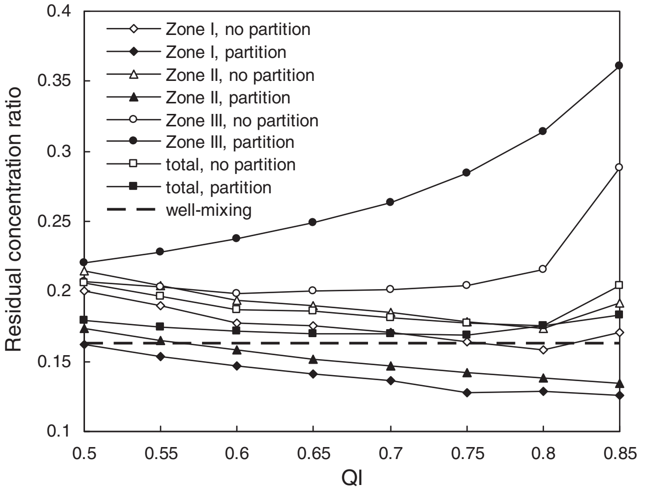


Fig. 10. The effect of QI on average pollution concentration for working region with and without partition.
Note: $A = 1\,\mathrm{m}^2$, QO = 0.75 and 6 ACH.

becomes very difficult to remove. Zone II was a region outside the ventilation stream; therefore, the total average pollutant concentration in the working region without partition would generally be higher than that with partition.

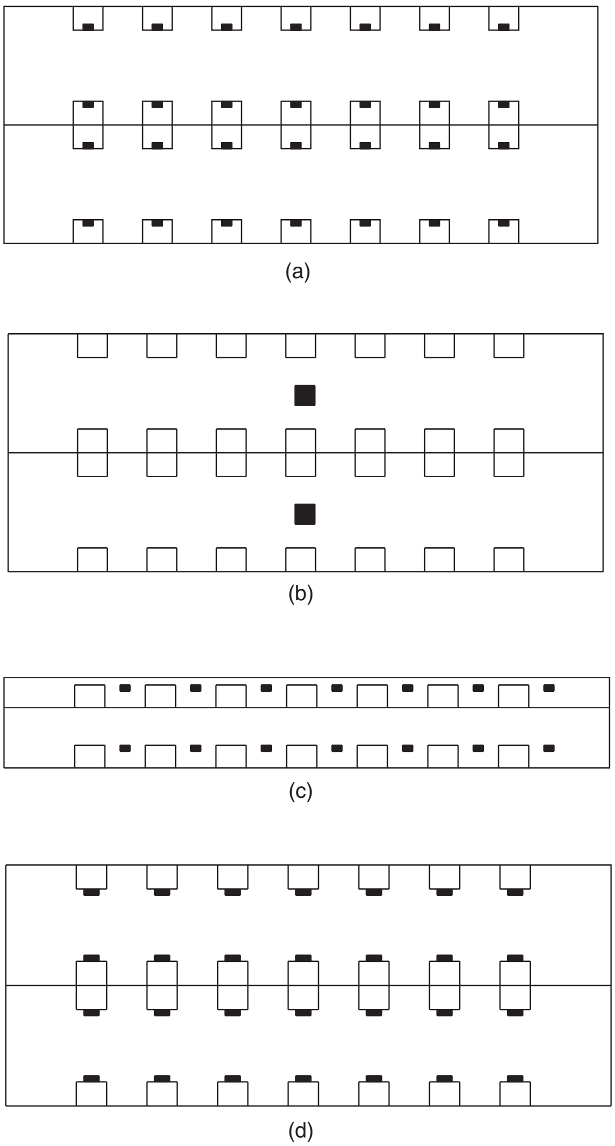
However, the total average pollutant concentration should not be the sole criterion to judge the applicability of a ventilation design. Average concentration in each zone should be checked constantly. Hence, for a general displacement ventilation with the present simulations, QI = 0.75 was recommended for application in the working region without partition, while QI = 0.5 or 0.55 was apposite for the working region with partition.

Local Exhaust Ventilation

In order to remove pollutant efficiently, it is essential to realise the flow field for general displacement designs. In this study, several local exhaust designs, as shown in Figure 11, were selected to study their applicability. The inlet positions and QI in local exhaust cases were the same as IG0 in Table 2. In Case1, the outlets were placed on the top surface of all the machines and the outlets' areas were at the same location as pollutant source. Case2 was based on previous general displacement ventilation but with additional two outlets on the roof to remove the pollutant in zones II and III effectively. The outlets in Case3 were on the wall between the two machines in order to remove the accumulated pollutant caused by circulating air flow. For Case4, the outlets were located on the ground ahead of machines.

Figure 12 shows the average pollutant concentration in the working region with and without partition that was associated with the local exhaust design. Case0 was the same as IG0 and was used as a control. With the outlets in Case1 being placed on top of the machine, the direct removal of pollutant would be expected. Both the total and zone average pollution concentrations for Case1 were the lowest, as shown in Figure 12. Besides, the total concentration of Case1 was lower than the well-mixing concentration and also lower than Case0. Figure 12 also shows that Case2 would be inferior to that of Case0. This was due to the fixed total ventilation rate; the more outlets incorporated would incur less air flow rate into each outlet. Also, the additional outlets of Case2 were too far away from the pollution sources.

As shown in Figure 5, a circulating flow prevails amid the two machines; this phenomenon could aggravate the



(a)

(b)

(c)

(d)

Fig. 11. Different designs of local exhaust ventilation: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

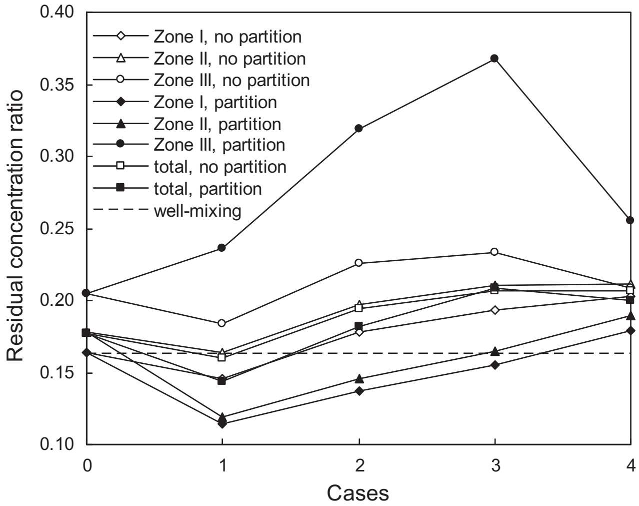


Fig. 12. The comparison of zone average pollution concentrations between working region with and without partition.
Note: $A = 1\,\mathrm{m}^2$, QI = 0.75, QO = 0.75 and 6 ACH.

pollutant accumulation and deteriorate the air quality considerably. Therefore, the original purpose of placing outlets amid these machines for Case3 was to improve the pollutant removal. However, the design had resulted with an unexpected outcome and the performance was worse than those in Case0, as shown in Figure 12. With a careful examination of the concentration/flow field near the outlets, most of the gases flowing out of the upstream outlets were actually fresh air. Hence, the retaining fresh air would lose its momentum to carry the downstream pollution. In addition, the distance between the outlet and pollutant source would inhibit the direct removal of the pollutant. For Case4, with the outlets located on the ground in front of the machines, the performance degenerated considerably, as shown in Figure 12. A high average concentration of the pollutant accumulated in zone I of Case4. Although the design of Case4 intended to conduct the pollutant along with fresh air towards the outlet situated on the ground, to restrict the pollution adjacent to the ground and prevent it from diffusing to zone II; however, the location of In1 was at a higher position with outdoor air blowing inclined downward this had led to some fresh air being directed towards upstream outlets (on the ground) without carrying any pollutant, thus acting likes a short circuit of an air flow.

The pollution concentration of zone III was as low as found for Case1, as shown in Figure 12. The outdoor air spurts horizontally into the upper working region of In2; and in this instance, there was no short circuit phenomenon. This was the reason why the average concentration of zone III was low in Case4. Nevertheless, locating the outlets on the ground would give rise to some problems and would be difficult to employ this in a practical situation.

Figure 12 shows that the total average concentrations for Cases2–4 which were all above the well-mixing concentration and exceeded that of Case0 (general displacement). The failure in those designs, suggested that the outlets should be placed adjacent to the pollution sources. Figure 12 also shows that the total average concentration in the working region with partition, which was lower than those without partition. However, the average concentration of the pollutant in zone III, in the working region with partition was obviously higher than

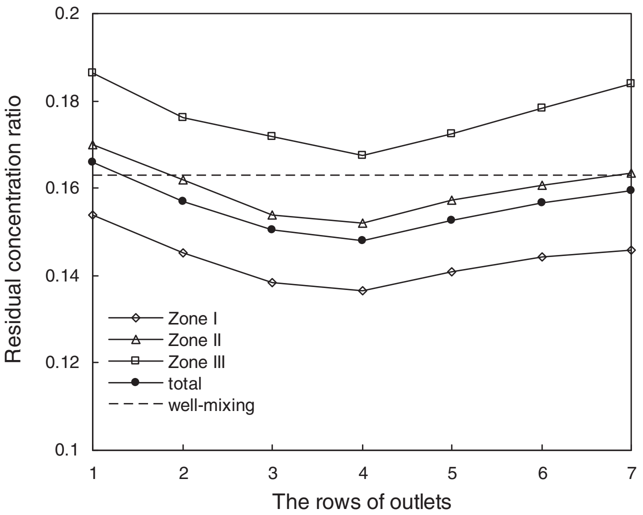


Fig. 13. For a local exhaust and without partition, the effect of outlet number on the pollution concentration.
Note: $A = 1\,m^2$, QI = 0.75, QO = 0.75 and 6 ACH.

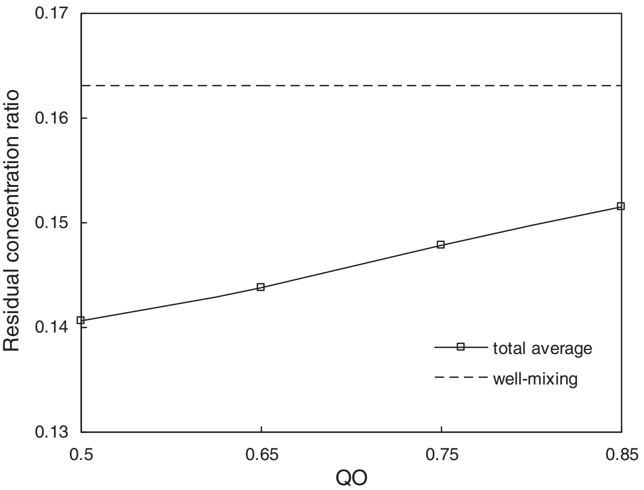


Fig. 14. For a local exhaust and without partition, the effect of QO on the total average pollution concentration of Case1, 4-row outlets.
Note: $A = 1\,m^2$, QI = 0.75 and 6 ACH.

that without partition. The results suggested that the upper and lower working regions should not be partitioned with local exhaust ventilation.

The pollution concentration in the downstream area was shown to be higher than that in the upstream because the air carried the pollutant away as it passed through the pollution sources.

It is worth investigating the effect of pollution removal which concentrated the outlets in the downstream region. The new designs would be based on Case1 (outlets on the top surface of the machines) with various number of outlets, and the results are shown in Figure 13. The abscissa of this figure was the "the rows of outlets", indicating only the number of downstream (or last) machine rows had outlets installed on them. The calculated results shown in Figure 13 illustrated the lowest pollution concentration found when the number of row was 4. Despite placing the outlets on all the machines would effectively remove the pollution generated from each of the machines, each outlet would possess only limited ability to pollutant removal and the rest of pollution could still be carried further downstream by the air flow. In fact, not only did the upstream outlet provide an exit for pollutant but also a way to drain the fresh air. In general, the amount of fresh air leaving from the outlet was much greater than the pollutant itself. Moreover, with a fixed total ventilation air flow rate, the flow rate of each outlet would decrease consecutively as the number of outlets increased. Therefore, the load of downstream outlets could be heavy (removing large pollutant by small flow rate) when the outlets are located on all the machines.

Table 3. The effect of QO on the pollution concentration in working region with partition

	Zone I	Zone II	Zone III	Total
QI = QO = 0.5	0.1392	0.1448	0.1839	0.1512
QI = QO = 0.75	0.1143	0.1186	0.2360	0.1442

4-column outlets, $A = 1\,m^2$, 6 ACH.

As shown in Figure 13, locating the outlets on downstream of the 4-row machines would give the best pollutant removal. Both the total and the individual zone pollutant concentrations were shown to be the lowest. Hence, this concept was further investigated to determine the influence of QO on the overall pollution removal when the working regions were not partitioned. Results of the simulation are given in Figure 14 with QI being fixed at 0.75. As shown in Figure 14, the total average pollution concentration decreased almost linearly relative to QO, and was significantly lower than the general displacement and well-mixing concentration. The forgoing investigation showed that the local exhaust type could still outperform the general displacement type in pollution removal. However, the conclusion of the superiority of the local exhaust type did not in full accord with that of Loomans [3]. This was because this study simulated the situation in a large plant, with a large number of pollution sources and a big pollution source area, where the pollution could diffuse out easily and was hard to capture.

The results presented in Figure 12 were generated when QI and QO were equal to 0.75. Figure 12 shows that the total average pollution residual concentration was about 0.14 when the working regions are partitioned. This value is about the same as the lowest value of the working regions were not partitioned (shown in Figure 14.). However, the average pollution residual concentration of zone III was about 0.23 in the working regions with partition; this was much higher than those without partition. The main reason was due to $QO = 0.75$. With the same pollution generation rate, the ventilation rates of the upper and lower working regions should be the same. Table 3 shows the average pollution concentrations of the working regions with partition when the row number of outlets is 4. The total average pollution concentration with $QI = QO = 0.5$ was higher than that with $QI = QO = 0.75$ but the average concentration in zone III was lower. The total average pollution concentrations of cases shown in Table 3 were not better than the best case as shown in Figure 14 (working region without partition).

From the above discussion, with the general displacement ventilation and in the working region without partition, the best pollution removal was obtained as $QI = 0.75$ with a negligible influence of QO was observed. In the conditions of general displacement ventilation and in the working region with partition, the total average pollution concentration was not the lowest one when $QI = 0.5$, but the average pollution concentration in zone III was the lowest. Hence, without loss of generality, the design with $QI = 0.5$ was a suitable design for the working region with partition.

In the conditions of local exhaust and working region with partition, the total average pollution concentration with $QI = QO = 0.75$ is lower than that with $QI = QO = 0.5$. However, for practical consideration, the presence of the lowest average pollution concentration in zone III when $QI = QO = 0.5$ may be essential. Therefore, a design with $QI = QO = 0.5$ will be recommended and the outlets are located on the top surface of those downstream machines. In the conditions of local exhaust and working region without partition, the best design is when $QI = 0.75$ and $QO = 0.5$ while the outlets are placed on the downstream 4-row machines.

In this study, the best way to ventilate an industrial metal processing plant within a large space building and having multi-pollution sources was investigated. However, even with the efforts made by the study, 14% of the pollution would still remain in the plant when the pollutant fraction was about 0.19, demonstrating the difficulty to remove all the pollution out of this kind of plant. Local exhaust type was shown to deliver a better pollution removal but was still not so effective. The ineffectiveness was due to not being able to freely locate the outlets due to practical limitation as discussed. Furthermore, some pollution would entrain into the large space of plant and would be hard to recapture.

Conclusion

This study numerically investigated the ventilation problem of a large space mechanical plant with multiple pollution sources. The types included: general displacement and local exhaust ventilation. The working region of the plant can be partitioned or non-partitioned. After analysing the flow and the concentration fields, the following conclusions and suggestions were made:

1. Large ventilation rate could improve the effect of pollution removal, but it could not remove the pollution thoroughly just by increasing the ventilation rate.
2. For the general displacement ventilation and working region without partition, the effects of outlet positions and their flow rates distribution had a negligible effect on the pollution removal. It is suggested that 75% of the total outdoor air flow rate should be used in the lower working region with the rest (25%) in the upper working region.
3. For the general displacement ventilation and with the working region being partition, it is suggested that the ventilation rates of the upper and lower working regions should be kept the same. This could therefore maintain a low pollution concentration in all zones even when the total average pollution concentration was not the lowest one when compared with others.
4. For the design with local exhaust type and working region without partition, the suggestion was to have QI and $QO = 0.75$ and 0.5, respectively. The outlets should be located on the top surfaces of those downstream of the 4-row machines.
5. For the local exhaust type ventilation and with the working region having partition, it is suggested that the ventilation rates of upper and lower working regions should be the same and the outlets should be put on the top surfaces of those downstream of the 4-row machines.

6. In a large plant space and with many pollution sources, there would be no big difference in performance between the best designs of general displacement and local exhaust ventilation types. One should consider the general displacement ventilation type and in the working regions without partition first then the local exhaust type ventilation and in the working region without partition.

The well-mixing concentration was a limit to the general displacement ventilation's achievement. One must carefully analyse and design the ventilation system to approach this value. A good local exhaust design should be able to limit the total average pollution concentration below the well-mixing concentration.

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