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Design of a Ventilation System for a Multistoried Warehouse

W.K. Chan **Y.W. Wong** **C.Y. Liu**

ABSTRACT

This paper presents experimental and numerical studies in the design of a ventilation system for a multistoried container warehouse and distribution center. A system based on uniform air change rate for the warehouse unit was ruled out due to the amount of fan energy involved in circulating air in a large space. The approach used was to ventilate the space at variable rates—6 air changes per hour (ACH) from floor level to a 3-m height, and at 1 ACH above that level. The studies show that a stratified system of 6-1 ACH as compared to a 6-0 ACH for a single warehouse unit provides good mixing of supply air as well as a minimum of dead spots. Investigation of the locations of the inlets also indicated that the optimal position for the 6-1 ACH is at a height of 3 and 5 m, respectively. Results on half- and full-wall analysis also show a greater mixing between adjacent units for the half-wall units. Effects of scaling have shown that model testing provides a good representation of flow pattern in the prototype.

Preliminary work on a pollution control system for the truck parking bay has indicated that the flow pattern around the truck exhaust system is enhanced by having the suction located near the exhaust of the trucks.

INTRODUCTION

The pressure to develop efficient warehousing facilities in land-scarce Singapore has led to the construction of multistoried warehouses. Provision of adequate ventilation systems on such a large scale has become a major concern for both owner and tenants in view of energy conservation, the comfort of the people working, and the well-being of the goods stored.

Design specifications of the ventilation requirements for enclosed spaces are generally given in the codes and standards established by various agencies such as ASHRAE and the building regulating authorities (Building Control Act 1989, ACGIH 1984). However, there are currently no guidelines for warehouse ventilation in the local codes (ACGIH 1984); ASHRAE recommends only a minimum rate of 6 ACH (Building Control Act 1989). Guidelines on the optimization of the system and on the conservation of energy are often lacking or insufficient; thus, designers are often required to rely on their experience when designing a ventilation system. In recent years, the concept of air stratification has become popular as a means of optimizing the effectiveness of the system and also of reducing the energy consumed (Skaret 1986). This concept relies on supplying air at different rates at different levels within the space; *i.e.*, more air is supplied where it is needed.

The object of the present study is to investigate the ventilation requirements of a six-story container freight station cum port warehouse facility. Its layout is one typically found in Singapore, and the building structure essentially consists of 32 warehouse units and 94 loading bays on the first story, 34 units and 106 bays on the second story, and 76 units and 232 bays on the subsequent stories. Each warehouse unit is 48 m by 13.8 m by 6.75 m, and a driveway connects all the stories. As a typical multistoried warehouse has many units on each story, it is common for the partitioning wall between two units to be solid up to a certain height followed by a wire-mesh partition above that level. In this paper, this type of wall is referred to as a half wall while the full wall refers to a solid full-height wall.

In the present study, the ventilation system design for a multistoried warehouse may be considered as three separate systems: a mechanical ventilation system for the warehouse units, a dilution air system for the access driveway, and a pollution control system for the truck parking bay. This paper presents results on the study of the mechanical ventilation system for the warehouse units and some preliminary findings on the pollution control system for the truck parking bay. The dilution air system for the access driveway is presently being investigated.

METHODOLOGY

The ventilation requirements for the prototype were designed based on a uniform air supply, a 6-1 variable air supply, and a 6-0 variable air supply, respectively. Although these designs provide information that could be checked during the construction, they do not provide information on the airflow within each warehouse unit.

In this situation, a scale model testing serves as a valuable design tool and enables rational design decisions to be made. The problem of scaling the results from the model to those of the prototype must, however, be taken into consideration (Skaret 1986). In addition, although model testings are essential, a detailed parametric study of the design variables is time-consuming and expensive. Numerical simulation techniques are used to study the flow

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W.K. Chan and **Y.W. Wong**, Senior Lecturers, and **C.Y. Liu**, Professor, School of Mechanical and Production Engineering, Nanyang Technological University, Republic of Singapore.

patterns. By comparing the results of the scale model testing and the computer simulation, valuable information on the design criteria was obtained. Further advantage is that a parametric study of the design variables can be conducted with minimal staffing and time. It must, however, be noted that numerical simulation is only as good as its capability to represent the real flow processes that it models.

The present study is based on the aforementioned approach. The computed results are compared with those of the model studies. Subsequently, numerical studies are conducted for all other variations.

EXPERIMENTAL STUDIES

For the prototype, it was proposed that a concept of variable supply rate be adopted, assigning an ACH of 6 for the space extending from the floor to a height of 3 m and 1 ACH for the upper portion of the unit. Subsequently, a 6-0 ACH was also tested. The locations of the supply inlets were also varied to study the optimal positions for minimal stagnation zones and flow uniformity.

Experiments were conducted on a 1:30 scale model, as shown in Figure 1. To model the flow conditions in the prototype as closely as possible, dimensionless analysis was performed to determine the controlling parameters for the model and the prototype.

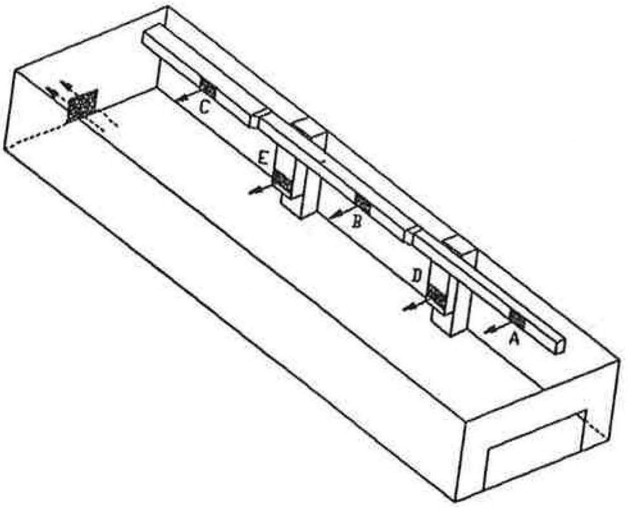


Figure 1 Schematic view of model

The controlling parameters were the number of air changes per unit time, the flow rate coefficient, and the Reynolds number (Lee 1990), which can be expressed, respectively, as:

$$\text{Air change per unit time} = Qt/L^3 \tag{1}$$

$$\text{Flow rate coefficient} = Q/VL^2 \tag{2}$$

$$\text{Reynolds number} = VL/\nu \tag{3}$$

where Q is the total flow rate, V the mean velocity, L the linear dimension of the body, t the time scale, and ν the kinematic viscosity of air. For complete similarity between the model and the prototype, Equations (1) through (3) must be applied.

Based on a 6 ACH for the lower level of the prototype, the flow in the prototype was calculated to be turbulent; thus, for dynamic similarity, the Reynolds number of the model must be greater than the critical Reynolds number (Schlicting 1968). The mean velocity of the model was found to be 2.4 times the mean velocity in the prototype. For the 1 ACH at the upper portion, similar calculations were carried out to ensure similarity. Based on this information and using the flow rate coefficient, the fan speeds selected for the lower and upper portions of the models were 1.99 m/s and 0.368 m/s, respectively. Although the overall Reynolds number of the model is only 3200 (less than the critical Reynolds number of 5300), the calculations were carried out assuming that the surfaces were smooth and that the beams, columns, and other flow disturbances were not taken into account. During the course of the experiment, it was realized that time played a very important role since the mean flow velocity in the model had increased, while the physical dimensions decreased, thus ensuring that the flow is turbulent. The model for the 6-1 ACH is illustrated in Figure 2. The above calculations for the model were repeated when the prototype operated at 6-0 ACH.

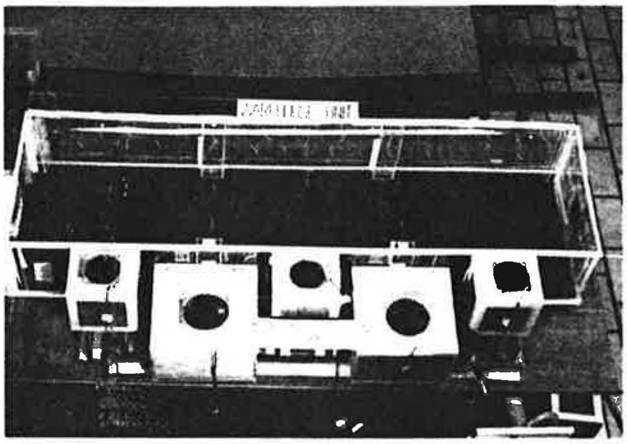


Figure 2 Experimental setup for 6-1 ACH

For a pollution control system for truck exhaust (Figure 13), an air removal method, whereby extraction hoods were placed as near as possible to the truck exhaust, was adopted. Based on an extraction air volume of 600 cfm for diesel engines, the requirements of the extraction system for the model was computed. The experiments were conducted with various combinations of 6-1 ACH or 6-0 ACH, full or half wall, and warehouse door open or closed.

NUMERICAL STUDIES

In designing the ventilation system of a warehouse unit and truck parking area, a commercially available software package is used to analyze the flow pattern of the model and the prototype (Rosten and Spalding 1986). The numerical simulation basically solves the equations governing the laws of conservation of mass, momentum, and energy. These can be expressed as:

$$\partial(\rho\phi)/\partial t + div\,(\rho V\phi - \Gamma_\phi\,\text{grad}\phi) = S_\phi \tag{4}$$

where ϕ is a general conserved property, Γ_ϕ is the exchange coefficient for ϕ, and S_ϕ is the source of ϕ per unit volume.

In the case of mass conservation, ϕ is unity. For the momentum equations, their ϕ's are u, ν and w, and the Γ_ϕ for velocities is μ_{eff}, effective viscosity. S_ϕ contains contributions such as the pressure gradient, gravitational force, gradients of velocities, and other relevant factors. For the conservation of energy, ϕ is the enthalpy and Γ_ϕ is the ratio of effective thermal conductivity to constant-pressure specific heat.

The space in question is divided into finite cells, and the finite volume equations are derived by integrating the differential equations over control volumes of finite size. These led to the development of a series of algebraic equations relating all the variables in the domain. The SIMPLE technique is employed to solve all these variables.

In the present study, numerical computation is conducted for both the model and the prototype, based on a constant turbulence model (Zurahim 1991). Comparing the numerical results and those of the experimental study, the general validity of the computed results may be verified before embarking on more complicated turbulence models. Another computer simulation on the prototype is also conducted. This enables the effects of scaling to be investigated.

Numerical experiments were then conducted on the prototype with various combinations of 6-1 ACH or 6-0 ACH, full or half wall, and warehouse door open or closed. Some simulations of the pollution control system for the truck exhaust were also carried out.

RESULTS AND DISCUSSION

The experimental and numerical results for warehouse units with half walls and a closed door are shown in Figures 3, 4, 5, and 6. The results indicate that the numerical simulated flow pattern agrees closely with that of the experimental flow pattern.

Figures 3 and 4 indicate that air from the supply inlets at a height of 3 m hits the wall and rebounds. Since the warehouse door to the left of the figures is closed, no air escapes, while some air flows out through the ventilating outlet on the right.

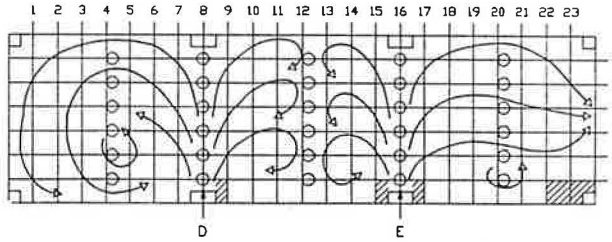


Figure 3 *Flow pattern for 1 unit, 6-1 ACH, door closed, and half wall (experimental result)*

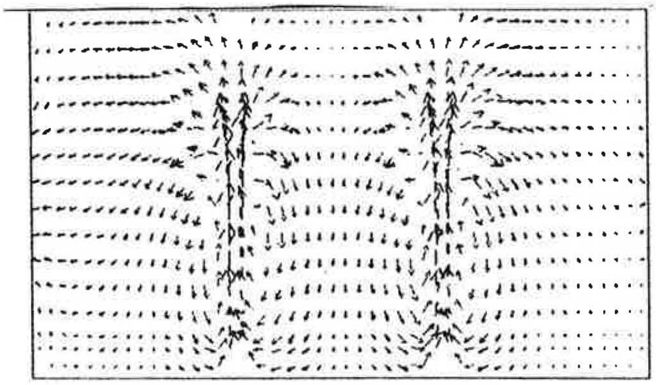


Figure 4 *Numerical simulation for 1 unit, 6-1 ACH, door closed, and half wall*

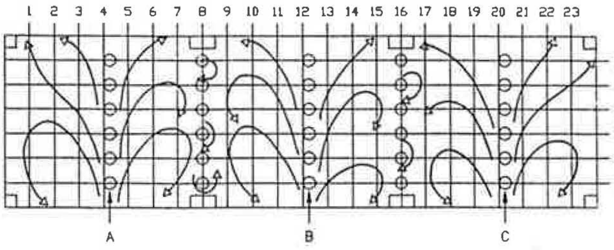


Figure 5 *Flow pattern for 1 unit, 6-1 ACH, door closed, and half wall (experimental result)*

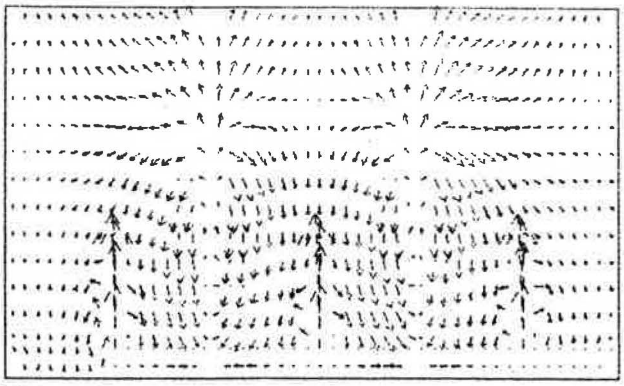


Figure 6 *Numerical simulation for 1 unit, 6-1 ACH, door closed, and half wall*

Similarly, for Figures 5 and 6, which represent the flow pattern at a height of 5 m from the floor level, the air exfiltrates into the adjacent unit when it reaches the far end since the partition separating the two units is only 4.5 m high. Thus, the results show that the numerical simulation closely predicts the experimentally observed flow patterns. The simulation results from the prototype and from the model also exhibit similar trends. However, the discrepancies between the calculated and the measured flow velocities can be as high as 30% for the peak velocities near the wall. The difference between these values may be attributed to the simplicity of the numerical modeling and the actual conditions at the fan inlet.

Results for the 6-0 ACH and 6-1 ACH are illustrated in Figures 7 and 8, respectively. The results indicate that flow stagnation occurs for the 6-0 ACH, while that of the 6-1 ACH achieves a good mixing of the air within the unit. The average velocities for the 6-0 ACH at a level of 2 m above

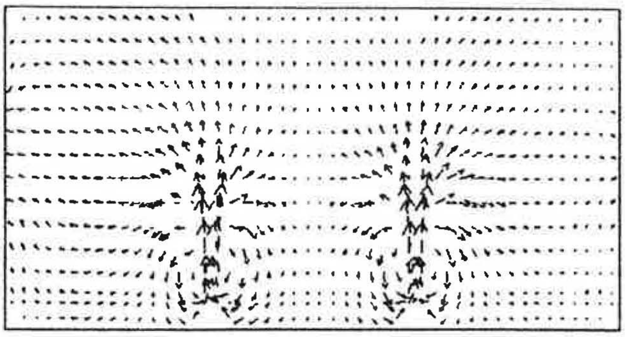


Figure 7 *Flow pattern at 2-m height for 6-0 ACH*

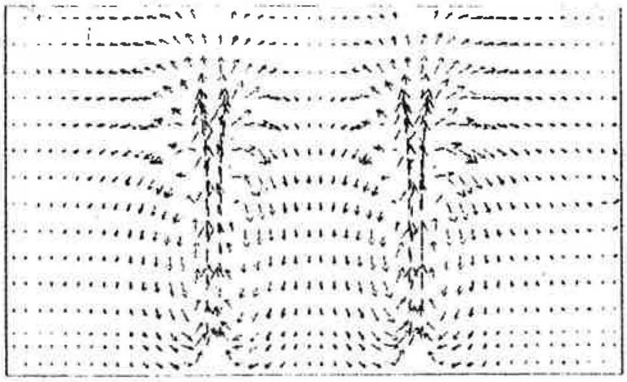


Figure 8 *Flow pattern at 2-m height for 6-1 ACH*

the floor is about 0.05 m/s as compared to 0.08 m/s for the 6-1 ACH. Flow visualization also indicated pockets of dead zones in areas away from the supply inlets for the 6-0 ACH case.

The results of the investigation on the location of the supply inlets are shown in Figures 9 and 10. When the supply inlet of 6 ACH is placed at a height of 2 m (Figure 9), the air tends to be deflected towards the floor and, in the process, it may collect dust and dirt before recirculating. In addition, the high-velocity air at this height may cause discomfort to the people working in the area. If the inlet is at a height of 4 m (Figure 10), most, if not all, the air will escape into the adjacent unit. This would defeat the purpose of ventilation system. Thus, as compared to the 2-5 and 4-6 designs, the location of the supply inlets at heights of 3 m and 5 m, respectively, represent the most satisfactory design in terms of air distribution and comfort with regard to the people working in the area.

Preliminary simulation results for the pollution control system and the flow pattern for the ceiling diffuser when a truck is in the parking bay are shown in Figures 11 and 12. The locations of the suction hoods for the truck exhaust and the ceiling diffuser are illustrated in Figure 13. With both the suction hoods and the ceiling diffuser operating, the flow pattern at the side of the parking bay is shown in Figure 11.

Flow from the diffuser moves vertically downwards and is directed to the suction hood. Along the centerline of the truck (Figure 12), the flow is relatively stagnant below the truck. Large recirculating zones are observed above the truck, because of the deflected air leaving the diffuser and hitting the top of the truck. From these results, the suction hoods can be considered as relatively efficient since, in general, the exhaust pipes of the trucks considered are located at the side. The exhausts will be sucked up by the suction hoods (Figure 11). However, a detailed study must be carried out on the dispersion and removal of the contaminant to ensure that the flow pattern of the contaminants follows that of the air movement.

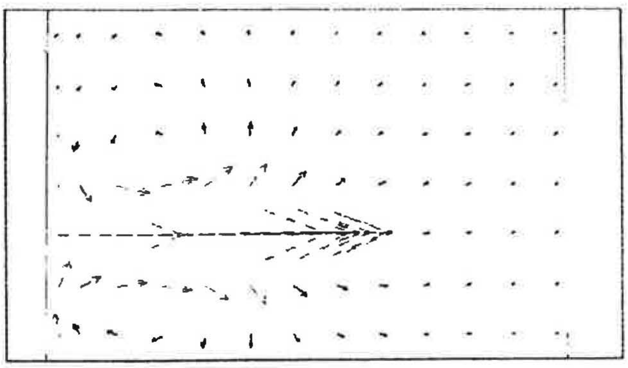


Figure 9 *Inlet supply at a height of 2-m (side view)*

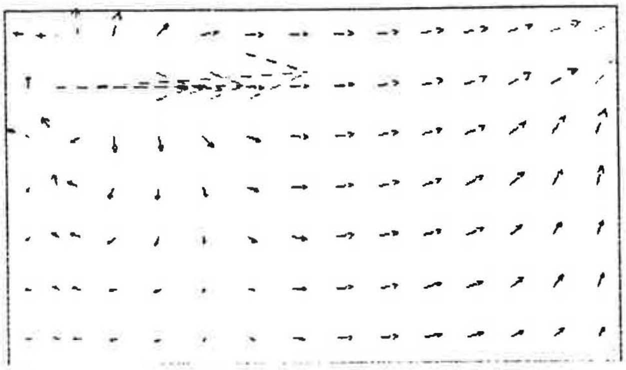


Figure 10 *Inlet supply at 4-m height (side view)*

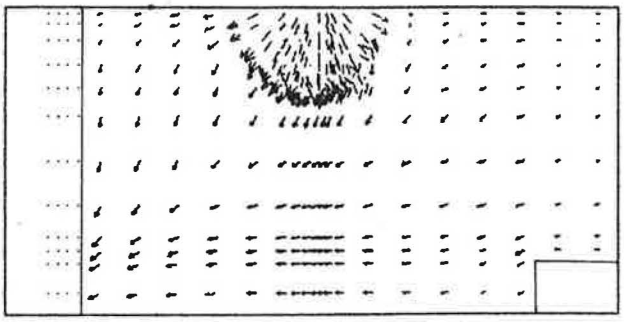


Figure 11 *Flow pattern at side of parking bay (side view)*

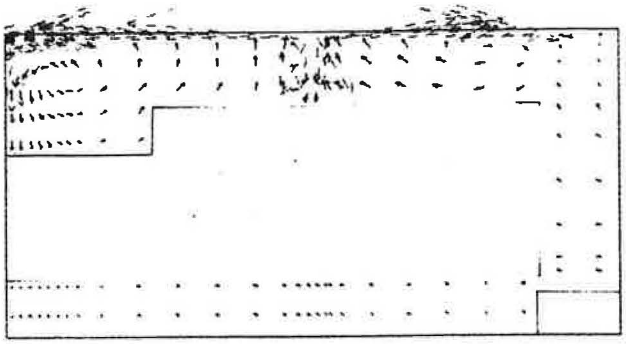
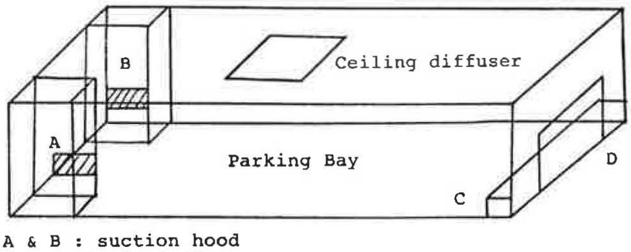


Figure 12 *Flow pattern along centerline of parking by (side view)*



A & B : suction hood
C : raised platform
D : warehouse door

Figure 13 *Schematic view of parking bay*

CONCLUSION

This paper illustrates the effectiveness of providing different air changes at different levels as a means of ventilating a warehouse storage unit. This concept also reduces the energy consumed. A 6-1 ACH at a 3-5 level was found to provide adequate ventilation with minimal dead spots. Preliminary research on the pollution control system has also shown that the suction hoods located near the truck exhausts are a promising solution.

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