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Improvement of Ventilation Flow inside a Large Factory Building Using PIV Velocity Field Measurements

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***Abstract*:** Air movement in workplaces, whether resulting from a forced ventilation system or natural airflow, has a significant impact on occupational health. In a huge building of shipbuilding factory, typical harmful factors such as fume or vaporized gas from welding and cutting of steel plates give an unpleasant feeling. From field data survey, the yearly dominant wind directions around the factory building tested were north-west, north-east and south-east. Among the three wind directions, the ventilation improvement was the worst for the north-eastern wind. This study was focused on modification of opening vents in order to utilize the natural ventilation flow effectively. Instantaneous velocity fields inside the 1/1000 scale-down factory building model were measured using a 2-frame cross-correlation PIV method. The factory model was embedded in an atmospheric boundary layer simulated in a wind tunnel. The modified vents improved the internal ventilation flow with increasing the flow speed more than two times, compared with that of present vents.

***Keywords*:** natural ventilation, wind tunnel, atmospheric boundary layer, PIV, velocity field.

1. Introduction

At the expense of economic development, the ventilation problems in industrial workplaces have been neglected for a long period of time. Air ventilation is responsible for intake, transport and removal of airborne hazardous substances. With recent emphasis on improving working environment of in-plant workplace, large efforts are being made to solve the industrial ventilation problems. Air movement in workplaces, whether resulting from forced ventilation or naturally occurring airflow, has a significant impact on occupational health.

In a huge building of shipbuilding factory, typical harmful factors giving unpleasant feeling include fume or vaporized gas resulted from a welding and cutting process, dusts from grinding and all sorts of noise. One of the best economic ways to reduce these harmful factors is to increase the efficiency of natural ventilation. It is very important to understand the internal ventilation flow in detail to provide a safe and comfortable working environment. The atmospheric wind condition, location and size of vents, ventilation devices, and arrangement of internal structures of the building affect largely the indoor ventilation of the building. For practical applications, a systematic investigation considering these parameters should be carried out. For example, the ventilation flow in a uniform flow is different from that in a building embedded in an atmospheric boundary layer.

Emswiler (1926) established the basic principles of building ventilation. This is still appropriate for present day applications. Kreichelt et al. (1976) reviewed the equations used for natural ventilation and compared the flow rate through a building with the flow rate calculated using various equations. Codiergues (1977) showed the effect of wind and heat release on natural ventilation in an industrial building. He developed a graphical technique that calculates ventilation rates for different heat releases and wind conditions.

Skaret (1978) examined the theory and practice of ventilation in industrial plants. On the other hand, Larsson (1978) has developed a procedure for numerical predictions of buoyancy-influenced re-circulating flow in a ventilated room and compared with experimental data. The isothermal and warm inflow cases were well predicted by the numerical method.

Most previous studies on industrial ventilation problem have been carried out for a simple 2-D building model using numerical simulations. A few field tests or laboratory experiments were performed with conventional point-wise velocity measurement instruments such as HWA (Hot Wire Anemometry) and LDV (Laser Doppler Velocimetry). However, these cannot give full flow field information for understanding the spatial variation of the ventilation flow inside a 3-D complex factory building. As far as we checked, there are no previous studies in the literature that resolve the environmental ventilation problems in a large factory building using a PIV velocity field measurement technique. In this study, the flow fields inside a factory building were investigated experimentally using a 2-frame PIV method (Lee, 2001). With a better understanding on the ventilation flow inside a factory model, the ventilation problem in the real factory can be resolved successfully.

2. Experimental Apparatus and Methods

2.1 Atmospheric Boundary Layer (ABL) and Factory Model

The atmospheric boundary layer (ABL) is formed as a consequence of interactions between the atmospheric wind and the underlying ground surface over time scales of one day or less. The depth of ABL varies from hundreds of meters to 2 kilometers. The present experiment was performed in a closed-return type subsonic wind tunnel having a test section of $6^L \times 0.6^H \times 0.72^W m^3$. The turbulence intensity is less than 0.07% at the free stream velocity of U_0 = 10 m/s. Spires and roughness elements were installed in front of the test section to simulate a thermally neutral atmospheric boundary layer. The schematic diagram of the wind tunnel test section and measurement system is shown in Fig. 1. The shipbuilding factory building embedded in ABL was scale-downed to 1/1000 and top view of the model is shown in Fig. 2. The Reynolds number based on the boundary layer thickness (d = 200 mm) was $Re = 1 \times 10^5$. It is well known that the onset of Reynolds number independence starts at about $Re = 1.2 \times 10^5$ for bluff bodies (Cermak, 1987). Although the low-turbulence free stream flow lowers the onset of independence slightly, there may be a little Reynolds number dependency in the present results. From wind engineering point of view, most small structures inside the building were neglected and some large structures were modeled with simplified configurations.

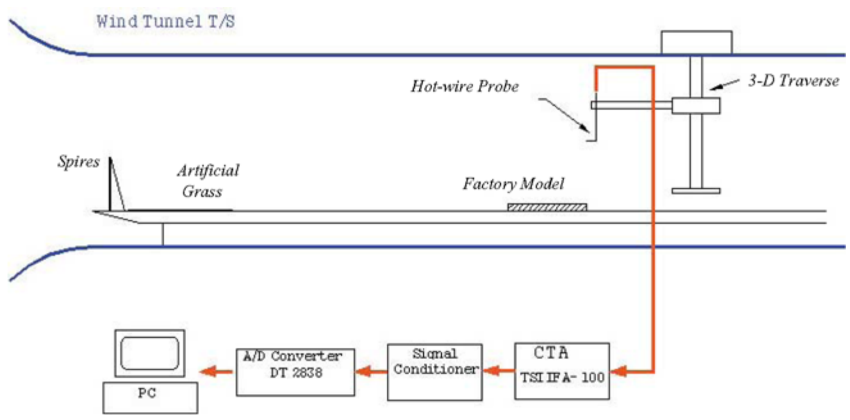


Fig. 1. Schematic diagram of experimental set-up.

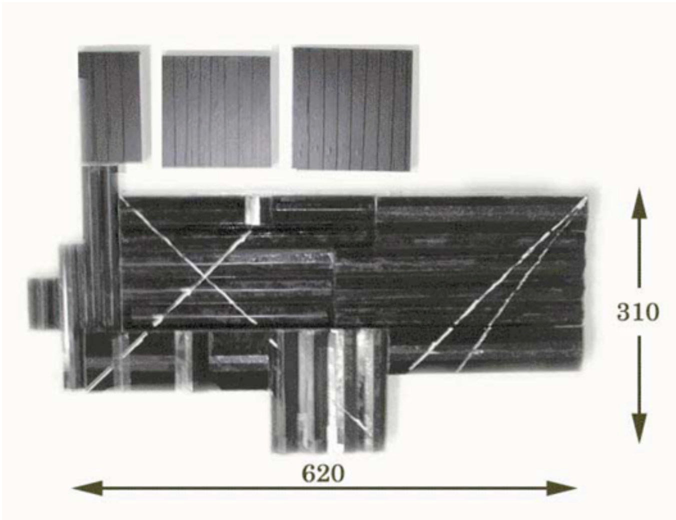


Fig. 2. Top view of the shipbuilding factory model and near-by 3 small buildings (unit: mm).

The velocity profiles of the simulated atmospheric boundary layer were measured by a hot-wire anemometry (TSI IFA-100). At each measurement point, 16,000 velocity data were acquired at a sampling rate of 2 kHz after low-pass filtering at 800 Hz. The mean velocity and turbulent intensity profiles measured at the location of the factory model, 4 m downstream from the leading edge of the test section, are shown in Fig. 3. The mean velocity and turbulent intensity profiles measured at several lateral positions (z) show a nearly similar shape. The turbulent intensity profiles were well matched with the atmospheric boundary layer in the real site.

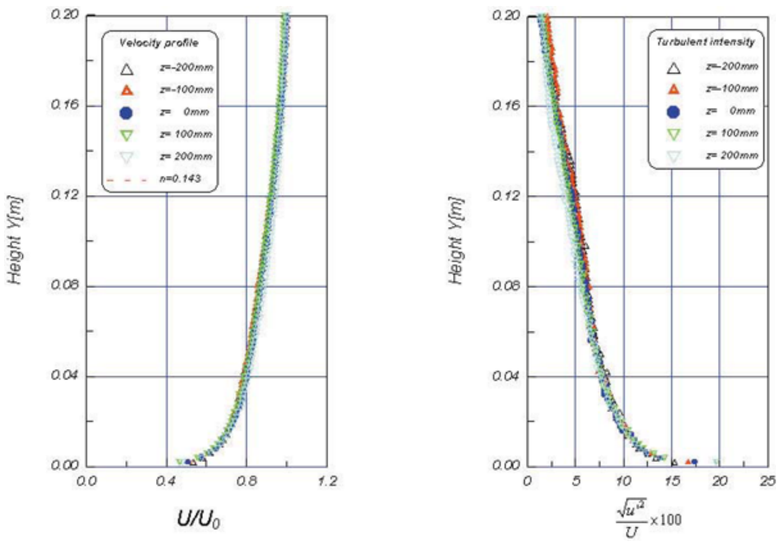


Fig. 3. Mean streamwise velocity and turbulence intensity profiles.

The mean streamwise velocity has the power law profile of $U(y)/U_0 = (y/d)^n$, here, d is thickness of the simulated ABL. The velocity profile is well fitted with $n = 0.143$, which corresponds to the velocity profile over an open terrain.

2.2 Wind Roses

The wind characteristics such as wind speed and dominant wind direction were analyzed based on the daily averaged wind data measured at the real site. Figure 4 shows the season-averaged wind rose. The periphery of the wind rose was subdivided into eight segments for indicating the wind directions. The annulus indicates the percentage of the wind rose probability. From the season-averaged wind data, we can find that the south-east, north-west and north-east wind directions are dominant wind directions around the factory building.

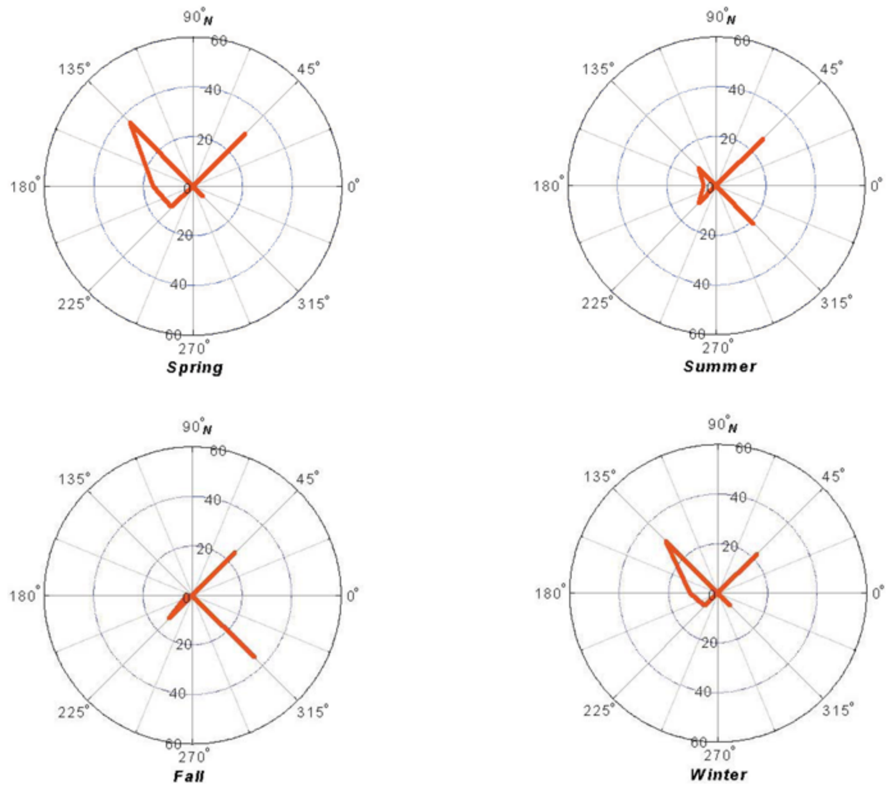


Fig. 4. Seasonal wind roses.

2.3 Velocity Measurement System

Instantaneous velocity fields inside the factory model were measured using a 2-frame PIV system. The velocity field measurement system consists of a two-head Nd:Yag laser, a high-speed CCD camera, a synchronizer and an IBM PC as shown in Fig. 5. The two-head Nd:YAG laser has 7 ns pulse duration and 25 mJ light intensity per pulse. The flow images were captured using a high-speed CCD camera (Speedcam+512) which can capture images at a sampling rate of 1000 fps (frame per second) with a full resolution of 512 × 512 pixels. Figure 6 shows the synchronization signal diagram for capturing particle images for velocity field measurements. For the velocity field measurements, the frame exposure time *Tf* was set to 25 ms. The time interval *Dt* between two consecutive frames was set to 25 ms using the v-sync signal from the high-speed camera. Details of the 2-frame PIV velocity field measurement system and its accuracy are described in Lee (2001) and Lee and Lee (2001). General description and practical guide for the PIV velocity field measurement techniques are well summarized in Raffel (1998).

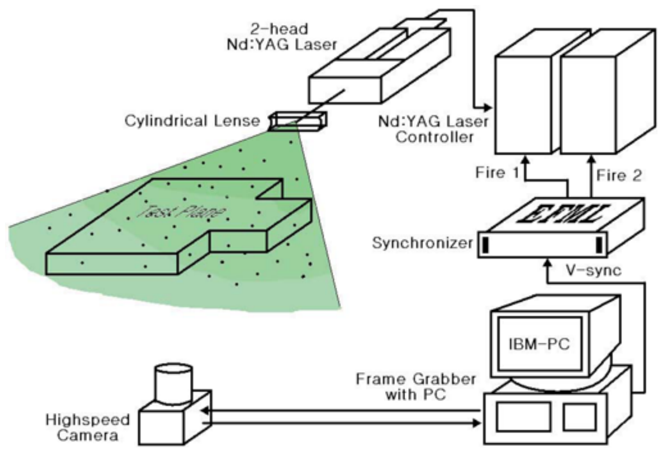


Fig. 5. PIV system for measuring velocity fields of ventilation flow inside a factory building.

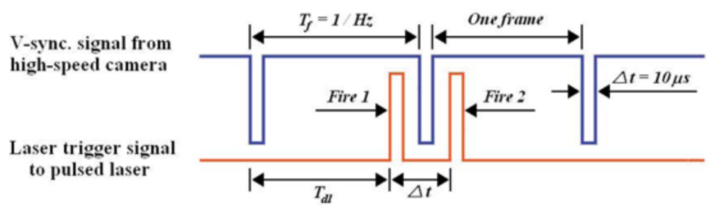
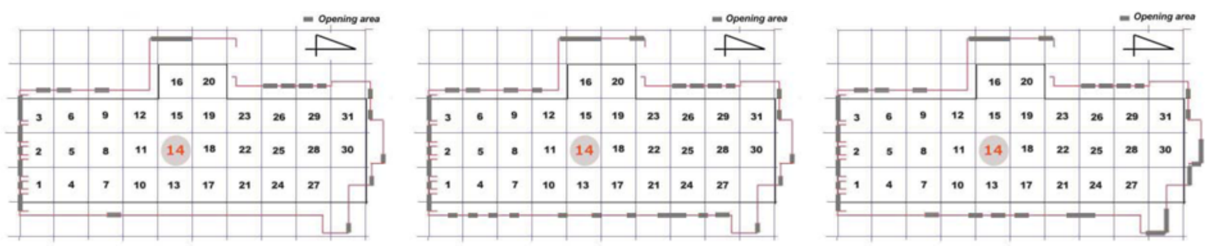


Fig. 6. Signal diagram for synchronization between the high-speed camera and a pulsed laser.

An olive-oil atomizer was placed in the settling chamber of the wind tunnel to seed scattering particles. The olive oil particles of 2 μm in mean diameter are sucked in by the high-speed compressed airflow. Because the field of view used for this study is small, the particle density should be as dense as possible. The atomizer gave the maximum particle generation at the airflow rate of 5.0 *l*/min.

In general, the field of view is determined from the experimental conditions such as camera resolution, laser light intensity and the tracer particle size. The horizontal plane at y = 6.5 mm in height from the ground was divided into 31 sub-sections as shown in Fig. 7. For each sub-section of about 60×60 mm^2, instantaneous velocity fields were measured for three wind directions; north-west, north-east and south-east. These wind directions were found to be yearly dominant around the factory building. Bold lines in Fig. 7 show the locations of the opening vents in the present and the modified factory models.



(a) Present factory model (b) Modified model (I) (c) Modified model (II)

Fig 7. Velocity field measurement sections with different arrangement of opening vents.

3. Results and Discussion

3.1 Ventilation System

The opening vents installed in the walls of the present and the modified factory models were compared at Table 1. Bold lines in the figure show the locations of the opening vents. For the case of the present model, the east-side wall is nearly blocked and several vents in the south- and west-side walls are opened. In the east and north sides, especially, there are lots of annex buildings such as offices and dining halls. In order to improve the natural ventilation, two modifications were suggested. In the modified model (I), several new vents are added on the east- and west-side walls at regular intervals and the galleries above the vents are expanded. However, it is practically difficult to remove present annex buildings at a regular interval. Therefore, in order to resolve this problem, one alternative is suggested to concentrate opening vents in the center region of the east wall and to utilize the yearly dominant north-east wind.

Table 1. Comparison of opening conditions tested in this study.

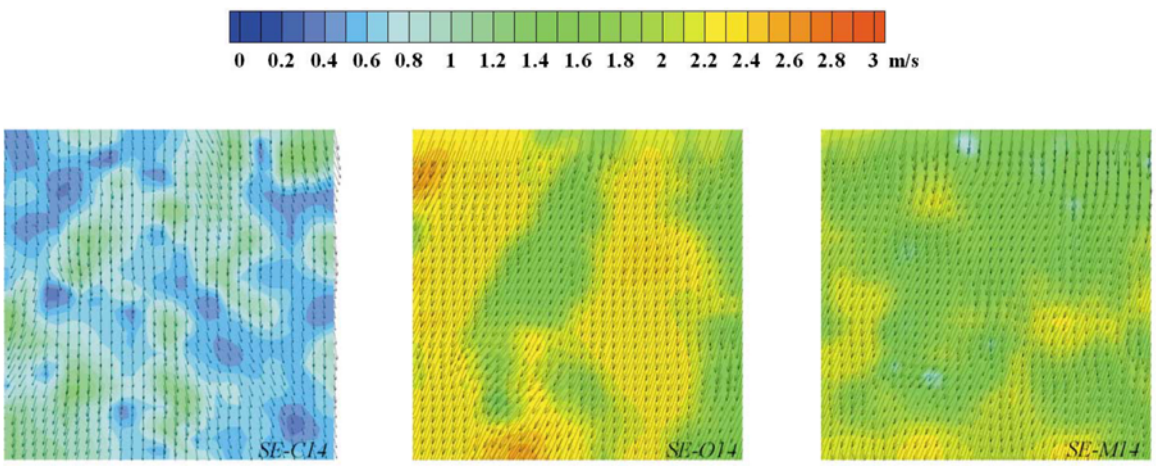
Present model	Modified model (I)	Modified model (II)
East : 1 opening West : 8 openings North : 5 openings	East : 10 opening West : 10 openings North : 5 openings	East : 6 opening West : 9 openings North : 6 openings
Total 14 vents	Total 25 vents	Total 21 vents

As a result, the indoor ventilation flow for this modified model (II) was revealed to be effective for improving the ventilation efficiency and to maximize the overall ventilation flow within the factory building.

3.2 Local Ventilation Flow

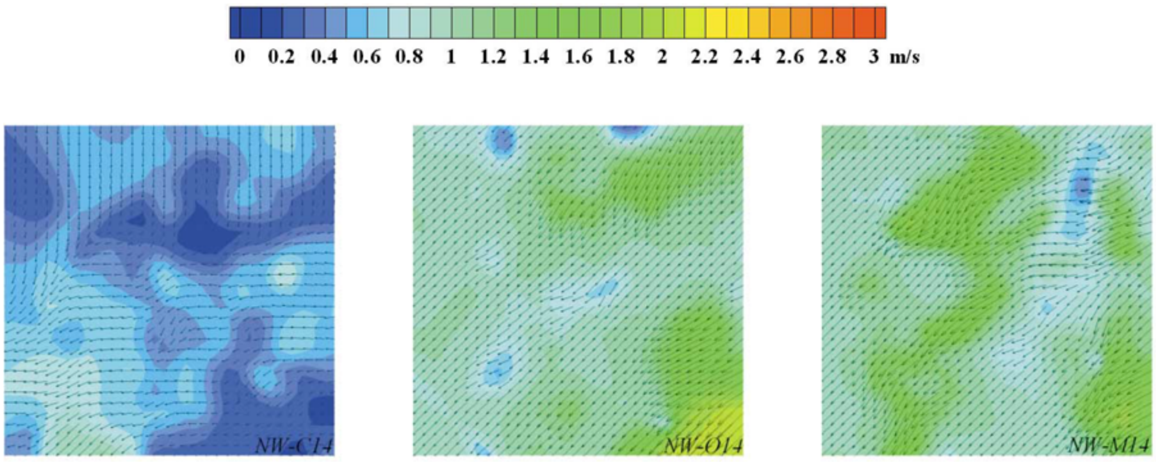
The velocity fields of ventilation flow for the present model and two revised models at the central sub-section No.14, where the dust emission is most severe within the building, were measured with varying the wind directions.

Figures 8, 9 and 10 show the instantaneous velocity fields at sub-section No.14 for the south-east, north-west and north-east winds. In these figures, the arrows and the gray contours of background indicate the velocity vectors and the flow speed, respectively.



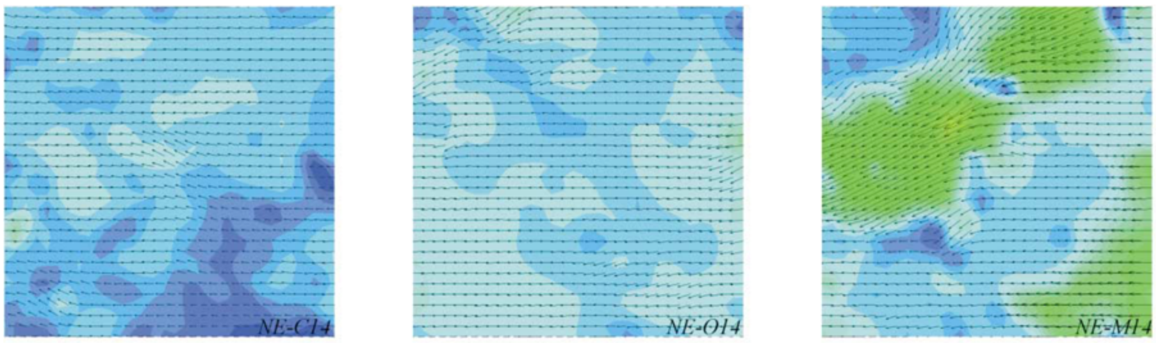
(a) Existing model (b) Modified model (I) (c) Modified model (II)

Fig. 8. Comparison of velocity fields at the central section No. 14 for south-east wind.



(a) Existing model (b) Modified model (I) (c) Modified model (II)

Fig 9. Comparison of velocity fields at the central section No. 14 for north-west wind.



(a) Existing model (b) Modified model (I) (c) Modified model (II)

Fig 10. Comparison of velocity fields at the central section No. 14 for north-east wind.

Figure 8(a) depicts the indoor ventilation flow for the existing factory model for the south-east wind. The outside air comes into the building through the vents in the south-east side walls and the inside air moves out through vents in the north-west side. The nearly stagnant flow appears at the sub-section No.14. For the case of models (I) and (II), however, the ventilation flow passes through the central section No.14 effectively with high speed as shown in Figs. 8 (b) and (c).

Figure 9 shows the instantaneous velocity fields for the north-west wind. As shown in Fig. 8(a), the ventilation flow inside the existing model still moves slowly. For the modified models (I) and (II), however, the flow speed is increased due to the air vent improvement. The modified models (I) and (II) show similar flow structure in the central section. This is attributed to the fact that they have nearly the same windward vents in the north-west side walls. From these results, we can see that the revised opening vents seem to utilize the atmospheric wind around the factory building effectively.

Figure 10 shows the instantaneous velocity fields at the sub-section No.14 for north-east wind. The flow field inside the modified model (I) doesn't show any large difference from the existing model. From this point of view, we can conjecture that the modified model (I) is not effective for the north-east wind. They may not contribute to exhausting the contaminants accumulated in the central region. The modified model (II) has opening vents in the central region of the east-side wall and they are facing directly with the large opening vents in the west-side wall. As shown in Fig. 10(c), the modified model (II) improves ventilation flow in the central section of the factory model and increases the overall airflow rate. From these results for three wind directions, the modification of the opening vents for the east and north walls is critical for increasing the overall airflow rate inside the building.

3.3 Overall Ventilation Flow

Figures 11 and 12 show the equal speed contours of instantaneous velocity fields inside the test building for the south-east and north-east wind directions. Since the total number of velocity vectors in the whole building is about 32000, it is difficult to get this kind of velocity field with a hot-wire or LDV system within a short period of time. There is no precedent study that analyzed the whole velocity field of ventilation flow inside a factory building immersed in an atmospheric boundary layer using a PIV system. Some local velocity fields at boundaries between two adjacent sections are partly mismatched. This is attributed to the combination of total 31 subsections measured at different instant into one. This indicates that the local velocity field may contain some random errors due to unsteady turbulent flow. However, we focused on the variation of overall flow structure for engineering diagnosis and the figures satisfy this objective clearly.

In the case of existing model for the south-east wind, the local flow near the south openings has relatively high speed. However, the flows near the east and north walls are slow and nearly stagnant. For the suggested models (I) and (II), the ventilation flow passes through the central region of the factory building with high speed as shown in Figs.11(b) and (c).

Figure 12 shows the velocity field in the whole building for the north-east wind. Comparing with Figs. 11 and 12, the modified models (I) and (II) show the effect of opening vents on indoor ventilation flow with respect to the wind direction. For the modified model (I), the effect of ventilation improvement on the north-east wind is not so good, even though it has more opening vents than the modified model (II).

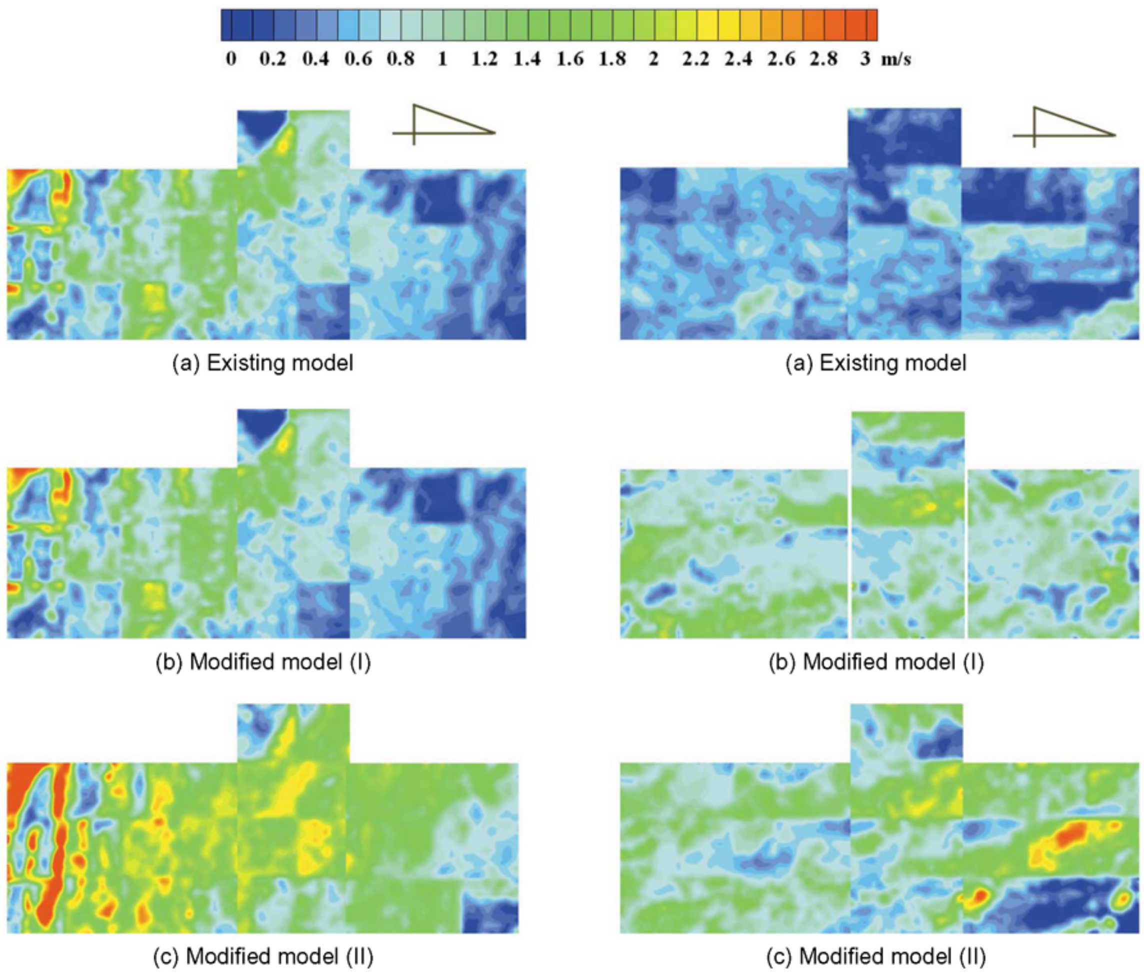


Fig. 11. Velocity fields inside the building model for south-east wind.

Fig. 12. Velocity fields inside the building model for north-east wind.

Figure 12 shows that the modified model (II) improves the indoor ventilation flow effectively with increasing the flow speed more than two times, compared with that of the present ventilation system. From a practical point of view, the modified model (II) seems to be the most effective and economic modification for improving the ventilation problem inside the factory building tested in this study. Reflecting these experimental results, the ship building company embarked and now under construction to modify the opening vents following the modified model (II).

4. Conclusion

The effect of opening vents modification on ventilation flow in a factory building was carried out. Instantaneous velocity fields inside a 1/1000 scale-downed factory model were measured using a 2-frame PIV system. The results are summarized as follows:

(1) The ventilation flow inside the factory building depends on the location and size of opening vents, building arrangement, and the wind environment such as direction and speed of atmospheric wind.
(2) For the present ventilation system, the opening vents are not effective except for the south- and west-side walls. The internal ventilation flow is slow and not effective to remove the dust particles in the central region.
(3) The modified model (II) improves the internal ventilation flow with increasing flow speed more than two times, compared with that of present ventilation system. The modified model (II) is an effective and economic modification to improve the present ventilation problem.

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