A Study on the Improvement of Ventilation Rate Using Air-flow Inducing Local Exhaust Ventilation System

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Abstract
In the case of the canopy hood, which is one of the existing Local Exhaust Ventilation systems, there appears to be a weakness in that when the level of ventilation is insufficient or when the effluent's buoyancy effect is significant, a partial amount of effluent seeps out and accumulates on the upper workspace. This study proposes the Air-flow Inducing Local Exhaust Ventilation system (AI-LEV), which can increase the ventilation rate without increasing the use of artificial energy by extracting the high-heat or high-density effluent that accumulates on the upper workspace. CFD (Computational Fluid Dynamics) was used to examine the effectiveness of the AI-LEV. The thermal characteristics of the mock-up chamber, along with the introduction of the canopy hood, was examined and the physical reproducibility of the CFD was verified experimentally. Compared to the existing Local Exhaust Ventilation systems, the introduction of AI-LEV led to a radical decrease in temperature through the overall interior. In addition, the high-temperature air that accumulated in the chamber's upper space was extracted smoothly outside the chamber through the inducement of the AI-LEV. The AI-LEV showed a 0.5-1.8 °C decrease in temperature in a space larger than 1.5m from the floor compared to the existing Local Exhaust Ventilation systems.

Keywords: local exhaust ventilation; thermal environment; mock-up; CFD

1. Introduction
Product manufacturing in factories tends to cause a range of contaminated substances, particles, high heat, and vapor to leak into the workspace. Therefore, factories use Industrial Ventilation to dilute or remove the effluent. Industrial Ventilation can be divided into General Ventilation and a Localized Exhaust Ventilation according to the ventilation range and method¹². Localized Exhaust Ventilation is used for the quick emission of high-density, high-heat effluent from the workspace.

The ACGIH (American Conference of Governmental Industrial Hygienists) provided detailed installation guidelines to Industrial Ventilation¹⁵. On the other hand, there are many cases of Industrial Ventilation being installed in small, low-capital workspaces according to the architect or constructor's field experience as well as previous experiences from similar equipment. Consequently, the problems of energy waste and deterioration of indoor air quality generally occur due to the excessive or insufficient ventilation rates, respectively. In addition, most small-scale workplaces do not choose the appropriate ventilation systems because of a lack of health awareness and strong punishment laws, and also due to financial reasons⁴⁵.

The following gives an overview of the major research on the Localized Exhaust Ventilation system, a type of the Industrial Ventilation. Huang et al.⁶ proposed a method to increase the appropriate exhaust flow rate and pollutant capture efficiency of a local exhaust hood using small-scale experiments. Witt et al.⁷ produced a new hood design using CFD (Computational Fluid Dynamics) that could increase the volume of fume capture. Yi et al.⁸ identified the flow characteristic of the ventilation system by CFD to improve the existing push-pull Localized Exhaust Ventilation system. In one proposal, the ventilation's flow performance was enhanced by a change in hood structure⁹¹⁵, and a method was developed to evaluate the performance rate of a Local Exhaust Ventilation system⁶¹⁸. Several studies reported measurements of the indoor air quality in kitchens using a local exhaust ventilation system⁹¹⁵.
The authors focused on factories, where products are manufactured using high-heat, and kitchens where food is cooked. Factories and kitchens are similar in that complex contaminants, such as high-heat, vapor and particles are released into the workspace atmosphere and there is a significant buoyancy effect. As shown in Fig.1., the effluent that occurs is collected and removed from the work area through a canopy hood, called Localized Exhaust Ventilation. On the other hand, when the rate of ventilation is insufficient or when the effluent’s buoyancy effect is significant, a partial amount of effluent seeps out and accumulates on the upper workspace. The effluent that accumulates in this way can eventually affect the workplace and harm the workers’ health. Therefore, the extraction of effluent on the upper workplace is essential in workplaces that use a canopy hood.

This study proposes the Air-flow Inducing Local Exhaust Ventilation system (AI-LEV), which can increase the rate of ventilation without increasing the use of artificial energy by emitting high-heat or high-density effluent that accumulates on the upper workspace. The effluent that accumulates in this way can eventually affect the workplace and harm the workers’ health. Therefore, the extraction of effluent on the upper workplace is essential in workplaces that use a canopy hood.

This study proposes the Air-flow Inducing Local Exhaust Ventilation system (AI-LEV), which can increase the rate of ventilation without increasing the use of artificial energy by emitting high-heat or high-density effluent that accumulates on the upper workspace. The purpose of this study was to investigate the actual performance of the AI-LEV. To achieve this purpose, CFD (Computational Fluid Dynamics) was used to analyze the improvement of temperature distribution and increase the ventilation rate in the workspace when the AI-LEV is used.

Prior to this experiment, the thermal characteristics of a workspace with the canopy hood system and the physical reproducibility of CFD were examined using a mock-up chamber experiment.

2. Air-Flow Inducing Local Exhaust Ventilation System

Fig.2. presents the conceptual diagram of the AI-LEV (Air-flow Inducing Local Exhaust Ventilation system). The AI-LEV is a system in which a separate exhaust outlet with a slightly larger diameter is added to the pre-existing exhaust outlet of a canopy hood, which is one of the existing Localized Exhaust Ventilation systems. The additional exhaust outlet acts as a tunnel that attracts the effluent accumulated on the upper area of the workplace when it is discharged from a pre-existing exhaust outlet. As a result, the final ventilation rate that is ejected from the AI-LEV increases, whereas the density of the workplace effluent and the air temperature decreases.

The AI-LEV’s canopy hood acts on the Localized Exhaust Ventilation, which is its original intention. The role of the added exhaust outlet, i.e., the AI-LEV’s exhaust outlet, is the general ventilation, where the effluent accumulates on the upper workplace of the room. As a result, the AI-LEV is a new form of ventilation system, in which general ventilation is combined with Localized Exhaust Ventilation.

Further investment in equipment, such as the installation of an additional exhaust fan in the workplace or an increase in the exhaust airflow rate, is unnecessary when using the AI-LEV. In addition, no extra artificial energy is needed because the AI-LEV is an inducement system that uses exhausted airflow. Therefore, it is an eco-friendly ventilation system.

3. Examination of the Local Exhaust Ventilation’s Thermal Characteristic

Before examining the performance of the AI-LEV, it is essential to examine the thermal characteristics of the existing Local Exhaust Ventilation. This was achieved by extensive experimentation using a mock-up chamber and a canopy hood (See Fig.3.). In addition, the physical reproducibility of the CFD analysis tool was compared with the experiment results. The reliability was a successful result for the AI-LEV’s performance investigation based on the results.

3.1 Experiment Overview

To reproduce a workplace that uses a canopy hood, as shown in Fig.3., a Mock-up chamber was constructed with a width, breadth and height of 3.92m, 3.96m and 2.47m, respectively. Two windows were installed to monitor the interior of the chamber, and the joints and gaps were also sealed to minimize air infiltration. Thirty-eight round holes with a diameter of 100mm were made in the lower part of the walls to allow for natural ventilation.

The canopy hood of the Local Exhaust Ventilation used in this experiment was installed according to ACGIH regulations. The distance between the hood and heat source was less than 1m, and the hood size was 600mm x 600mm, which is 300mm greater than
the heat source. The centrifugal fan used for ventilation was connected to a duct, 200mm in diameter, for a forced exhaust. The local exhaust rate of the canopy hood was calculated using equation (1) proposed by the ACGIH. When the heat source reached 250 °C and the interior condition was 26 °C the exhaust ventilation rate was approximately 637.8 m$^3$/h (0.177 m$^3$/s). The experiment used a gas-burning appliance as the heat source. The gas-burning appliance was heated by manually controlling it to allow the soybean oil in the iron pot to reach 250 °C.

$$\frac{Q_t}{L} = 0.06b^{1.33}\Delta t^{0.42}$$  \hspace{1cm} (1)

where $Q_t$ is the total ventilation requirement (m$^3$/h), $L$ is the length of the square hood (m), $b$ is the width of the square hood, and $\Delta t$ is the temperature difference between the heat source and the exterior air.

### 3.2 Measurement Conditions and Method

The space outside of the mock-up chamber was moderated at a temperature of 26 °C using a room air-conditioner. The air volume emitted from the hood was checked continuously using an air-flow meter (accuracy ±3%, ±10m$^3$/h). The temperature and air velocity around the hood was checked using a multi-channel anemometer (accuracy ±1%, ±0.1m/s), and the interior and exterior temperature of the chamber was measured using a T-type thermo-couple.

The temperature and the air velocity between the iron pot and hood were measured, as shown in Fig.4. A total of 59 measurement points were also measured at intervals of 0.11m - 0.15m widthwise and 0.1m - 0.2m lengthwise. The temperature and the air velocity measurements were performed after installing a multi-channel anemometer widthwise; they were measured 10 times in total. Prior to each round of measurements, the heating power of the gas burning appliance was again controlled manually to allow the temperature of the soybean oil to reach 250 °C. Accordingly, manual control of the gas burning appliance was carried out 10 times. To prevent the human body affecting the experiment, the experimenter exited the chamber after installing the multi-channel anemometer. The measurement was performed at 5-second intervals for 15 minutes. The average of the 5-minute data, starting 10 minutes after the start of the measurement, was used as the result value.

### 3.3 CFD Analysis Overview

Commonly used software, STAR-CCM+ 9.06, was used for CFD analysis. The Standard K-Epsilon Model was used as a Turbulence Model, Segregated Flow was used as a Physical Model, and the First-Order Upwind Scheme was used as the scheme in CFD Analysis. In addition, convective and radiative heat transfer was analyzed. Radiation analysis was performed using the S2S Thermal Radiation model$^{22-23}$ of Star-CCM+. For the object analysis space, a mock-up chamber, canopy hood and heat source were reproduced, as shown in Fig.6. The analysis grids were divided into approximately 300,000 grids.

The results obtained from the experiment were used for the boundary conditions for CFD. During the experiment, the gas burning appliance was manually controlled in order for the temperature of the soybean oil to reach 250° C. The fireball temperature of the gas-burning appliance could not be measured due to the limitations of the measuring equipment. Therefore, the surface temperature of the heating sources, which are the iron pot, soybean oil and the fireball from the gas burning appliance was calculated using equation (1).
The heat transfer coefficient of the chamber wall was 0.4 W/m²K. The air temperature and pressure of the supply inlet were each 25.5 °C and 0 Pa. The air velocity of the exhaust outlet was 5.63 m/s (637.8 m³/h) in the exhaust outlet of the canopy hood.

3.4 Experiment and CFD Analysis Results

Fig.7 shows the temperature distribution results according to the experiment and CFD analysis. Although the 250 °C heat from the heat source was emitted through the hood, thermal stratification formed in the interior of the chamber. This is the result of the high-temperature effluent escaping sideways from the hood and accumulating on the upper area of the chamber. The danger of thermal stress to the worker exists because high-temperature heat of approximately 30 °C forms around the hood.

The experiment difference was high around the heat source with the temperature of the experiment and CFD at approximately 0.2-10.1 °C. The remainder of the measurement points showed little difference with 0.1-1.8 °C. The large difference in heat around the heat source was caused because the soybean oil that was heated by the gas-burning appliance was controlled manually. The temperature of the heat source was impossible to control accurately because it was done manually. As a result, more heat is considered to have been emitted than the targeted 250 °C of the heat source.

Fig.8 shows the results of the air velocity distribution according to the experiment and CFD analysis. In the space between the heat source and the hood, the experiment revealed an air velocity that was approximately 0.01-0.54 m/s higher than in CFD. The actual heat value in the experiment was considered to be higher than the CFD's boundary condition level because the heat source was controlled manually. As a result, the thermal plume in the experiment was a much greater factor than in CFD. In the remaining areas, the difference in air velocity was small at 0.01-0.07 m/s.

The experiment revealed a higher interior temperature and air velocity than in the case of CFD because the experiment's heat source was controlled manually. Nevertheless, the use of a gas-burning appliance is essential to eject the high-temperature effluent continuously. Therefore, the current experimental conditions appear to be valid, despite the limitation of manual control. Both the experiment and CFD demonstrated a heating stratification inside the chamber. This heating stratification was formed as a result of high-temperature effluent escaping sideways from the hood. The physical reproducibility between the experiment and CFD analysis was confirmed.

4. Examination of the Air-Flow Inducing Local Exhaust Ventilation Performance

4.1 CFD Analysis Overview

Fig.9 presents the object analysis space installed with the Air-flow Inducing Local Exhaust Ventilation system. The size and physical quantity of this section's object analysis space is identical to those of the object analysis space in chapter 3. The AI-LEV is a system, in which an exhaust outlet with a larger diameter duct is added to the exhaust outlet of the canopy hood. While the effluent collected by the hood is ejected through the exhaust outlet of the canopy hood, the additional exhaust outlet of AI-LEV induces the effluent
accumulated on the upper workplace and extracts it (See Fig. 10.).

When the diameter of the canopy hood's exhaust outlet is \(a\), and that of the AI-LEV's exhaust outlet is \(b\), the amount that is induced and extracted differs according to the \(b/a\) rate, (i.e., the AI-LEV's exhaust outlet diameter rate). As the induced ventilation rate increases, there will be a marked decrease in the various effluent and high-temperature air that accumulates in the upper workspace. Table 1 lists the analysis cases according to the \(b/a\) rate. The existing Localized Exhaust Ventilation using only a canopy hood with a \(b/a\) rate was set as the Base Model. The diameter \(a\) of the canopy hood's exhaust outlet was set to 20cm. Cases 1-4 have gradually increasing \(b/a\) rates of 1.3-2.0.

The CFD analysis models, the convective and radiative analysis of CFD, the CFD scheme, and the CFD boundary conditions are the same as those described in Chapter 3. The air velocity at the exhaust outlet of the canopy hood is 5.63 m/s. The pressure at the exhaust outlet of AI-LEV was set to 0 Pa. Therefore, air outflow or inflow may occur in the exhaust outlet of AI-LEV according to the pressure distribution in the surroundings. The air temperature and pressure at the supply inlet were set to 25.5 °C and 0 Pa, respectively. The heat transfer coefficient of the chamber wall was 0.4 W/m²K. The analysis grids increased due to the expectation that the pressure distribution surrounding the exhaust outlet of the AI-LEV would be extremely high. As a result, the total analysis grids were divided into approximately 400,000-450,000 in number.

### 4.2 CFD Analysis Results

Table 2 lists the analysis result of each case. An examination of the interior temperature distribution of the chamber shows that in the Base Model, high-temperature air, more than approximately 30 °C, forms extensively near the space from the chamber's upper area to the entrance of the hood. For Cases 1 and 4 with AI-LEV, however, it showed that the air temperature was lower than the Base Model. Cases 1 and 2 adopting AI-LEV, which had comparatively low \(b/a\) rates, showed a significantly lower air temperature of the overall space compared to the Base Model.

The air velocity distribution in the chamber was similar in all cases. On the other hand, the air velocity distribution around the AI-LEV’s exhaust outlet showed a difference according to the \(b/a\) rate. In Cases 1 and 2, where the \(b/a\) rate was comparatively low, the high-temperature air that accumulated in the upper area was induced by the AI-LEV and extracted outside the chamber. On the other hand, in Cases 3 and 4, which had comparatively high \(b/a\) rates, the high-temperature air in only some parts of the AI-LEV was induced and ejected. In other parts of the AI-LEV, the exterior air was induced to form an eddy.

The eddy prevented the high-temperature air from being induced and extracted smoothly. In particular, in Case 4, where the \(b/a\) rate was highest, the greatest eddy formed around the exhaust outlet of AI-LEV. The exterior air flown in through the exhaust outlet gave little relief to reducing the temperature inside the chamber because it was unable to enter the chamber but rather hovered around the exhaust outlet of the AI-LEV forming an eddy.

Fig. 11. shows the vertical temperature distribution at a location with a distance of 0.3m from the hood. In the Base Model, the temperature at 1.5m in height, which is the height of the hood entrance, was 29.2 °C, while the temperature at 1.9m was at 31.1 °C. In Cases 1 and 2, where the \(b/a\) rate was comparatively low, the temperature was approximately 1.2 °C lower at 1.5m and approximately 1.8 °C lower at 1.9m than the Base Model. On the other hand, in Case 4,
where the $b/a$ rate was highest, the temperature was approximately 0.7 °C lower at 1.5m and 0.5 °C lower at 1.9m compared to the Base Model. Each case showed little difference in temperature at 0.1m-1.3m, while producing a difference of approximately 0.5 °C with the Base Model. Compared to the existing Localized Exhaust Ventilation, the AI-LEV showed a temperature decrease of 0.5-1.8 °C, 0.5 °C in spaces smaller than 1.5m and greater than 1.5m, respectively, without the use of additional artificial energy.

Fig.12. presents the ventilation rate induced and extracted according to the $b/a$ rate. As there is no induced ventilation rate for the Base model, which has a $b/a$ rate of 1, it is shown as zero. Case 2 with a $b/a$ rate of 1.5 showed the highest induced ventilation rate. This was followed in order of the highest induced ventilation rate by Case 1, Case 3, and Case 4. In other words, the induced ventilation rate does not increase with the size of the exhaust outlet's diameter in the AI-LEV.
Equation (2) was calculated using the results in Fig.12, where $x$ is the AI-LEV's $b/a$ rate, and $y$ is the induced ventilation rate ($m^3/s$). The correlation coefficient between the $b/a$ rate and induced ventilation rate was very high at approximately 0.98. In this equation, the induced ventilation rate was highest when the $b/a$ rate was 1.4. Therefore, equation (2) and the CFD results show that the highest induced ventilation rate can be obtained when the $b/a$ rate is approximately 1.4-1.5.

5. Conclusion

In the case of the Canopy hood, which is one of the existing Local Exhaust Ventilation systems, there is a weakness in that a partial amount of effluent seeps out and accumulates on the upper workspace when the rate of ventilation is insufficient or when the buoyancy effect of the effluent is significant. Therefore, this study introduced a new Air-flow Inducing Local Exhaust Ventilation system (AI-LEV). The AI-LEV is a new form of ventilation, in which general ventilation is combined with a Localized Exhaust Ventilation system. In this study, the validity of AI-LEV was assessed using CFD. Prior to this, the thermal characteristics of a workspace with the canopy hood system and CFD's physical reproducibility was analyzed through a Mock-up chamber experiment.

The conclusions for this study are as follows.

1) While examining the Localized Exhaust Ventilation's thermal characteristic, heating stratification was identified experimentally and CFD analysis. The heating stratification was formed by the effluent that had escaped laterally from the hood. The physical reproducibility between the experiment and CFD analysis was confirmed.

2) When the AI-LEV was adopted, a radical decrease in temperature developed in the overall interior in comparison to the existing Localized Exhaust Ventilation. The occurrence was particularly greater in Cases 1 and 2, where the $b/a$ rates were comparatively low.

3) In Cases 1 and 2, where the $b/a$ rates were low, the high-temperature air that accumulated in the upper area was induced by the AI-LEV and ejected smoothly outside the chamber. On the other hand, in Cases 3 and 4, which had comparatively high $b/a$ rates, an eddy formed to hinder the high-temperature air from being smoothly induced and extracted.

4) Compared to the existing Localized Exhaust Ventilation, the AI-LEV produced a temperature decrease of 0.5-1.8 ºC in a space larger than 1.5m from the floor.

5) This study proposed a correlating equation using the AI-LEV's $b/a$ rate and the induced ventilation rate. This equation and the results of CFD showed that the highest induced ventilation rate can be obtained when the $b/a$ rate is approximately 1.4-1.5.

6) The AI-LEV had the effect of decreasing the interior temperature and increasing the ventilation rate without the need for additional artificial energy or increasing the physical capacity of the ventilation fan.

The limitations of this thesis are as follows.

1) The equation of the induced ventilation rate (Equation (2)) proposed in this study was derived under limited conditions. For this equation to have a general relationship, it will be necessary to review the exhaust velocity of the canopy hood and the diameter of its exhaust outlet under a range of conditions. Therefore, further research on this will be required.

2) A first-order upwind scheme was used as the differencing scheme for CFD. Therefore, a truncation error may have been included in the CFD results. To enhance the quality of the analysis results, it is more desirable to use a second or third-order scheme.
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