DEPARTMENT OF ENVIRONMENT SYSTEMS

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MASTER'S THESIS

STUDY ON THE DISTRIBUTION OF CHEMICAL CONCENTRATION IN AN EXPERIMENTAL LABORATORY WITH LOW-VELOCITY DOWNFLOW VENTILATION

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Chapter 1 Introduction

1.1 Introduction to Indoor Air Pollutants

1.1.1 General Indoor Air Pollutants

Indoor Air Pollutants (IAP) refers to the existence of pollutants, and can be classified into four categories: organic, inorganic, biological, and radioactive[1], including particulate matters ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), CO_2, CO, NO_X, SO_2, ozone, radon, toxic metals, and microorganisms. The three primary sources of IAP are: (i) outdoor air pollutants, (ii) personnel density and activity, and (iii) construction materials, equipment, and furniture[2].

Numerous researches have investigated ventilation schemes in different indoor environments, such as offices[3], lecture rooms[4], aircraft cabinets[5], operation rooms[6], laboratories[7], etc. Depending on the occupants and activities being performed, each of these interior ambient has distinct safety standards or priorities. For example, the importance of ventilation systems implementing in the aircraft cabinets increased in the context of COVID-19[8]. The cabin of an aircraft is an enclosed space with a high occupant density, low humidity, and low air pressure[9], and the design of airflow distribution is also constrained by a number of criteria in confined construction[10] and somatosensory considerations[11].

Another instance of vital importance of airflow distribution that has been extensively explored is the operating room. In operation rooms, the surgical staff are the primary source of airborne pathogenic particles, and the ventilation system is the primary technique employed to eradicate such infection agents[12]. The researchers may give much more consideration on the surgical staff, the surgical equipment, the lamp, as well as staff work practices, clothing systems. Sasan's research summarizes different ventilation systems applied in the operation room, including turbulent mixing airflow ventilation, vertical (ceiling) airflow systems, horizontal and mobile Laminar Airflow (LAF) systems, displacement ventilation systems and hybrid ventilation systems[13]. Yet years of research also arouse controversy among infection specialists, engineering technicians, and ventilation professionals. For instance, despite the existing international standard recommending that LAF systems be implemented in operating rooms, recent research have shown that adopting LAF systems provides little benefit[14]. Designing an efficient ventilation system for an

operation room is complicated and requires careful consideration of a wide range of technical, logistical, and ethical issues. The insight we obtained from the operation rooms may help facility professionals design and operate airborne contaminant control system in other indoor ambient.

1.1.2 Laboratory Air Pollutants

Laboratory refers to a facility where the “laboratory use of hazardous chemicals” occurs. It is a workplace where relatively small quantities of hazardous chemicals are used on a non-production basis (OSHA CFR n.d.). This definition excludes workplace where commercial quantities are produced. However, this does not eliminate the threat of airborne hazards for laboratory staff. About 40% of laboratory personnel's time is spent in the laboratories. And with the gradual advancement of experimental research in highly sophisticated domains such as medication, optics, and nuclear. Experimental study will investigate an increasing number of synthesis and development, and herein reveals new risks. Some of these risks are plainly visible, such as VOCs, particulate matters, radioactive materials, physical hazard that may cause explosive, flammable, combustible, oxidizer effects. The study revealed that when benzene was utilized in the laboratory, personnel were exposed to dangerous concentrations that exceeded the Short-term Exposure Limit (STEL) in any of the 15-minute intervals assessed at any temperature[16]. Epidemiologic studies have also implicated laboratory workers in an elevated risk for various types of cancer, including lymphoma, leukemia, brain tumors, pancreatic cancer and breast cancer[15].

However, the toxicological properties of some new materials are not currently well recognized. In the field of nanotechnology, the number of publications on nanoparticles has expanded dramatically over decades yet less than 1% are concerned with the biological impact of nanoparticles[17]. The evaluation of the risks associated with certain nanoparticles has not kept pace with the development of novel materials, much alone applicable legislation and standards. In all countries, CO_2 concentration is employed as a control indicator for mechanical ventilation. CO_2, on the other hand, should not be considered an indoor pollutant as it is odorless, colorless, and less hazardous than VOCs. Today, with the rapid development of analytical technology, greater emphasis should be placed on pollutant indicators such as VOCs, formaldehyde, $PM_{2.5}$, bacteria, etc.

1.1.3 Typical Laboratory Protective Practices

In the safety hierarchy shown in Fig. 1.1., elimination and substitution are two priorities. Hence, laboratory occupants are recommended several “prudent practices” known as Green Chemistry such as: (i) Purchase the least quantity of chemicals necessary. (ii) Use safer chemical alternatives such as chemical which is less toxic or harmful. (iii) Conduct microscale experiments. In situations where we are unable to avoid the use of dangerous substances, engineering controls are especially crucial. Laboratory ventilation is one type of engineering controls. Considering that roughly half of the electricity utilized in a typical laboratory is attributable to ventilation, reducing the ventilation rate could significantly cut energy usage[18]. Therefore, it is essential to investigate ways to minimize the ventilation rate for energy savings while maintaining a safe laboratory environment.

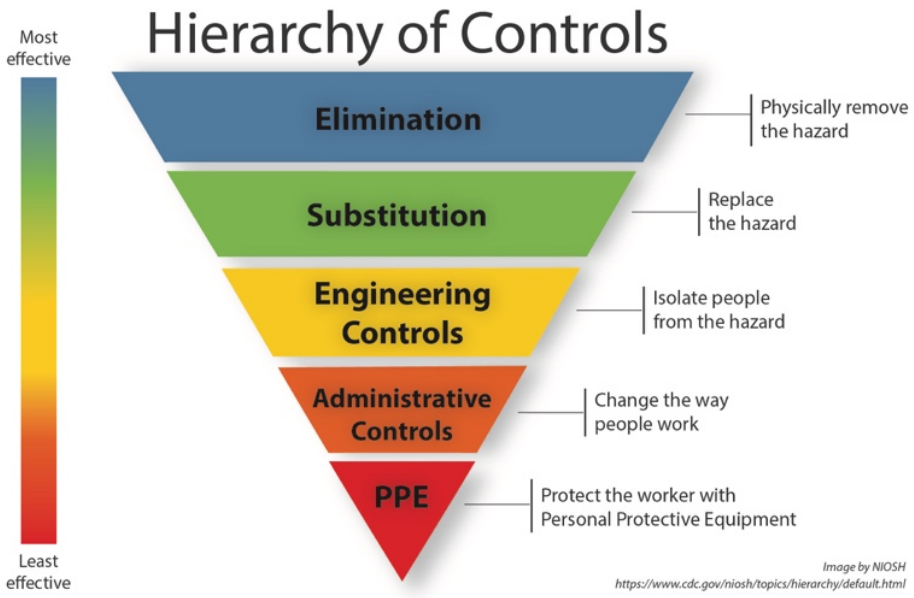


Fig. 1.1. Hierarchy of controls (NOISH 2016)

One of the important IAP within indoor ambient that menaces indoor occupants is VOCs[2]. Among different indoor environments, laboratories tend to expose individuals to higher risk of VOC emissions during experiment tasks with various sources, including measurement, reactions, transfers, dumping, and other handling of hazardous substances[16]. The risk of exposure to airborne hazardous chemicals generated during experiment activities can range from negligible to extreme, depending on the types of hazardous chemicals, the quantities of reagents, the characteristics of reaction, the duration of exposure, the compliance level of work

protocol, engineering controls, and other physical factors within the laboratories over time (temperature, humidity, luminous intensity, etc.)[19]. Typically, laboratories that conduct activities about polymer synthesis, organic/inorganic synthesis tend to require the highest level of protection for airborne chemical hazards.

Strategies for mitigating overexposure to chemical hazards in laboratories (Fig. 1.2.) include (i) the control of emission source, (ii) exposure control devices, and (iii) laboratory ventilation systems[20].

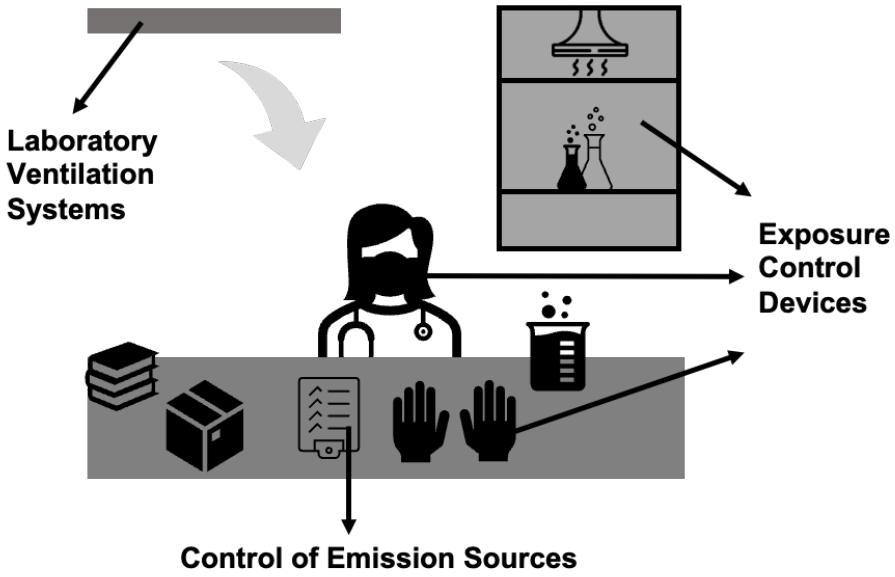


Fig. 1.2. Illustration of three strategies for mitigating overexposure to chemical hazards in laboratories

Control of Emission Sources

In terms of the control of emission sources, such actions include precautionary measures on chemical hazards, effective hygiene plan, etc.

Exposure Control Devices

Regarding exposure control devices, laboratory fume hoods and Personal Protective Equipment (PPE) are a common tool for dealing with gases(vapor) and aerosols (particles, smoke, mists, etc.) contaminants. However, a fume hood is not able to handle all scenarios because the interior surfaces may become coated with particles or mists. In certain circumstances, other equipment such as an enclosing hood (e.g., glovebox, biosafety cabinet) or a local exhaust hood (e.g., floor-mounted hood,

perchloric acid hood, dustless hood, snorkel) may provide more acute protection. It is important to note that the location of fume hoods or other vented openings directly influence the ventilation performance. Personnel within laboratories should consider the spatial layout associated with safe ventilation. Concerning PPE, personal protective equipment or apparel are necessary to prevent aerosol inhalation or skin absorption. The common practices such as double chemo-therapy gloves, protective gown, eye/face protection or respiratory protection should be available in laboratories with hazardous chemicals.

1.1.4 Standards on Laboratory Ventilation Systems

Laboratory ventilation systems are generally established or agreed upon by owners and may refer to current standards. For general occupational safety, Occupational Safety and Health Administration (OSHA) explicitly categorizes the hazards of all chemicals produced or imported and specifies the communication protocol to employers and employees in Permissible Exposure Limits (PELs) (§1910.1200)[21]. And the requirements within are designed to be compatible with the provisions in the Nations Globally Harmonized System of Classification and Labelling of Chemicals (GHS)[22]. For occupational safety concerning with laboratory scale activities, OSHA sets forth the occupational exposure to hazardous chemicals in laboratories in PELs (§1910.1450)[21]. Other standards include ANSI/AIHA Standard Z9.5-2022: Laboratory Ventilation[23], NFPA 45: Standard on Fire Protection for laboratories Using Chemicals[24] and NIOSH 2016 (NOISH List of Antineoplastic and Other Hazardous Drugs in Healthcare Settings, 2016)[25], or guidelines provided by ASHARE[19]. These standards and guidelines aim to help different stakeholder groups involved in laboratory ventilation issues.

Different stakeholders, for example, laboratory occupants and building managers, have different priorities or emphasis. Laboratory occupants tend to consider worst-case operation or lapsus in work practices, thus seldom making adjustment on physical ventilation attributes such as airflow rate. The building managers, on the other hand, may confront energy considerations and carbon reduction initiatives. And herein lies a potential conflict. To address this contentious issue, some studies are focusing on energy-efficient programs for researchers through clarifying what they "*need"* and what they *"want"*. McCarthy et al. introduced a control banding process to help different stakeholders determine their risk level[26], [27]. AHARE also sets a *Classification of Laboratory Ventilation Design Levels* to help classify, design and

operate laboratory ventilation systems complying with current and prospective laboratory activities[19].

1.1.5 Mechanisms of Gas Dispersion

The gaseous contaminants spread into the environment once emitted. The local change in the concentration of a gaseous substance in a flow field is influenced by three main factors: advection caused by the velocity field, the diffusion caused by concentration gradients and the body forces caused by gravity (Buoyancy). The advective force caused by the airflow field is a more effective dispersion mechanism. The typical turbulent coefficients in gases caused by the flow field are normally 2 orders of magnitude lager than the molecular diffusion coefficient[28]. In terms of the body forces, the dense differences are often ignored in the indoor environment research. If, on the other hand, the gases that are released have a particularly high density or are released in large quantities, or if ambient environment is very calm, then the local density perturbations should also play a meaningful role in the dispersion behavior[28]. Take the calculation of acetone below as an example.

In a simplified model, the law of conservation of mechanical energy, which is given below, can be used to estimate how gravity would affect a gas and air mixture.

$$V = \sqrt{2gh} \tag{1}$$

For a gas-air mixture (ignoring viscous resistance and further dilution), the estimation can be written as

$$V = \sqrt{2\frac{g(\rho_{mix}-\rho_a)}{\rho_{mix}}h} \tag{2}$$

- g: the gravitational acceleration (m/s^2),
- h: the falling height (m),
- ρ_{mix}: the density of the gas-air mixture (kg/m^3),
- ρ_a: the density of the air (kg/m^3).

Given acetone as the targeted dense chemical in this study, the average density of the mixture of 200 ppm concentration and the corresponding falling velocity at the height of 1.2 m can be calculated as follows,

$\rho_{Acetone\ at\ 25℃}$ = 2.368 kg/m^3
$\rho_{Air\ at\ 25℃}$ = 1.184 kg/m^3
c_{mix} = 200 ppm = 0.02 % (vol.) (acetone concentration).

$$\rho_{mix} = \frac{0.02}{100} \times 2.368 + \frac{99.98}{100} \times 1.184 = 1.18424 \text{ kg/m}^3$$

At the height of 1.2 m,

$$V = \sqrt{2\frac{g(\rho_{mix}-\rho_a)}{\rho_{mix}}h} = 0.070 \text{ m/s}$$

In this example, the falling velocity at the height of 1.2 m with 200 ppm concentration of air-acetone is 0.07 m/s (ignoring viscous resistance and further dilution), which means the gravitational body force should not be ignored in the dispersion when the airflow velocities are as low as 0.1 m/s.

1.1.6 The Types of Laboratory Ventilation System

There are two prevalent types of airflow distribution organization in the chemical laboratories: the mixing ventilation system, and the displacement ventilation system, as is shown in the Fig. 1.3. More advanced ventilation systems, such as temperature-controlled ventilation systems and mobile LAF systems etc., are frequently implemented in indoor situations that demand a higher level of cleanliness, such as sterile rooms and operating rooms. University laboratories may continue to emphasize a certain degree of practicality and prudence in their operation. Having a reliable and cost-effective ventilation system is, thus, crucial from a point of view of engineering control.

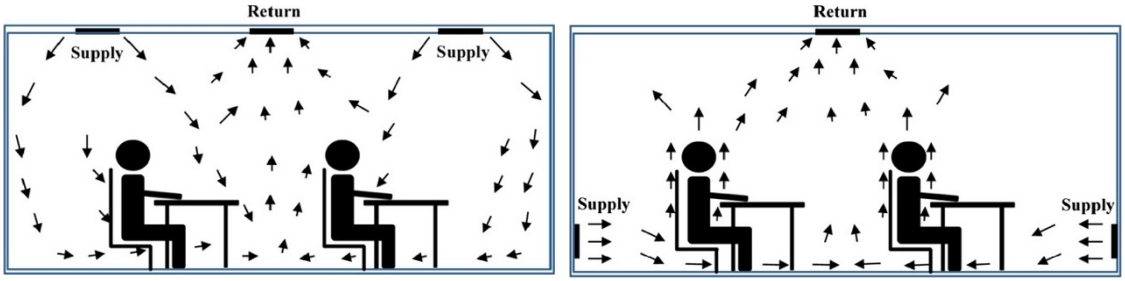


Fig. 1.3. Schematic of the mixing ventilation with ceiling supply and ceiling return (left) , and the displacement ventilation with antipodal supply at low level and ceiling return (right)[29].

Mixing ventilation system

The goal of mixing ventilation, also known as high-velocity ventilation, is to feed air with a high momentum ($> 1\ m/s$) into an indoor environment such that the air mixes and the heat or pollution load in the space is reduced.

Displacement ventilation system

The displacement ventilation system uses density differences to dissipate undesired heat or pollutants, or to establish a particular flow pattern. Typically, lower-temperature fresh air is given to the lower zone of a room. The vertical temperature stratification causes a variation in air density, thus allowing heat and contaminants to rise to the upper zone of the room, where the exhaust opening is placed. The difference with the mixing ventilation system is that the velocity of the supplied air is usually lower than 0.2 m/s.

Yet a number of VOC contaminants are generally of high relative density to air, as is shown in Table 1.1[28]. As we calculated above, the dense gas gravity effect should not be ignored in low-velocity indoor environment.

Table 1.1.

List of properties of VOC-based contaminants[28]

Chemical Grouping	Material	Molecular Formula	Molar mass (gr/mol)	Density* (kg/m^3)	Boiling point (°C)	Odor Threshold (ppb)
Ketone	Acetone	C_3H_6O	58.08	2.39	56.5	4580
Aldehydes	Hexanal	$C_6H_{12}O$	100.16	4.12	131	13.8
Aromatics	o-Xylol	C_8H_{10}	106.17	4.37	144.5	490
Alcohols	Benzylalkohol	C_7H_8O	108.14	4.45	205.3	5550
Esters	n-Butylacetat	$C_6H_{12}O_2$	116.16	4.78	126.1	6.6
Terpene	α-Pinen	$C_{10}H_{16}$	136.24	5.61	155	692
Alkanes	n-Decan	$C_{10}H_{22}$	142.29	5.86	174.1	741
Glycol ether	2-Butoxyethanol	$C_6H_{14}O_2$	118.18	7.04	171	0.97
Glycol ester	Butoxyethoxyethyl-acetat	$C_{10}H_{20}O_4$	204.27	8.41	245	1.6

* Densities are given for 23°C. The density of air at this temperature is given as 1.19 kg/m^3.

1.1.7 The Importance of Laboratory Ventilation Systems

Ventilation systems are the primary and efficient means of removing contaminants in indoor spaces. General laboratory ventilation relies on dilution to remove airborne contaminant generated during the laboratory-scale activities. Designing a general ventilation for a laboratory is, however, complicated. The purpose of general

laboratory ventilation is threefold: it must (i) help control the airborne chemical hazards below levels that may cause harm to occupants (acute or chronic effects, cancer etc.), property (corrosion, chemical residue), and environment (pollution, chemical accumulation), (ii) provide proper temperature and humidity for the occupants and the general experiment tasks conducted on the bench-top, and (iii) energy efficiency through commensuration with the level of risk to airborne contamination.

The design of laboratory airflow organization should efficiently regulate the indoor airflow flow direction, such that air flows from clean areas to polluted areas, in order to offer laboratory personnel with a safe and comfortable working environment. Available research on the form of laboratory airflow organization focuses solely on mixed ventilation and replacement ventilation. Neither the applicable domestic nor international laboratory standards nor the existing research specify the form of airflow organization for laboratories. And the ventilation effect of displacement ventilation in laboratory settings has not been well investigated.

1.2 The Objective of this Study

Despite the precautions taken to ensure the air quality in the laboratory, for example, the use of higher minimum air flow rates, additional fume hoods and explicit laboratory operating protocol, laboratory air quality need more research to clarify uncertainties on general and local airflow conditions. Numerous researches work on indoor ventilation simulations so far, yet less attention has been paid to local airflow pattern around the emission source from chemicals, especially on the bench-top, where laboratory occupants spend their time conducting various experiment processes.

Given that a number of VOC-based contaminants are generally of higher density than air, it is important to pay attention to the concentration distribution of dense gaseous contaminants and their transport behavior under efficient ventilation schemes. This study was determined to investigate the ventilation performance of a novel downflow ventilation implemented in an experimental laboratory. The experiment began from two perspectives: supply air volume and exhaust locations and utilized one typical dense chemical to determine how these two factors influenced the airflow pattern in the breathing zone and in the vicinity of the contamination source. Additionally, CFD and PIV measurements in the local scale were utilized to investigate the spatial characteristics of the airflow in the breathing zone, and

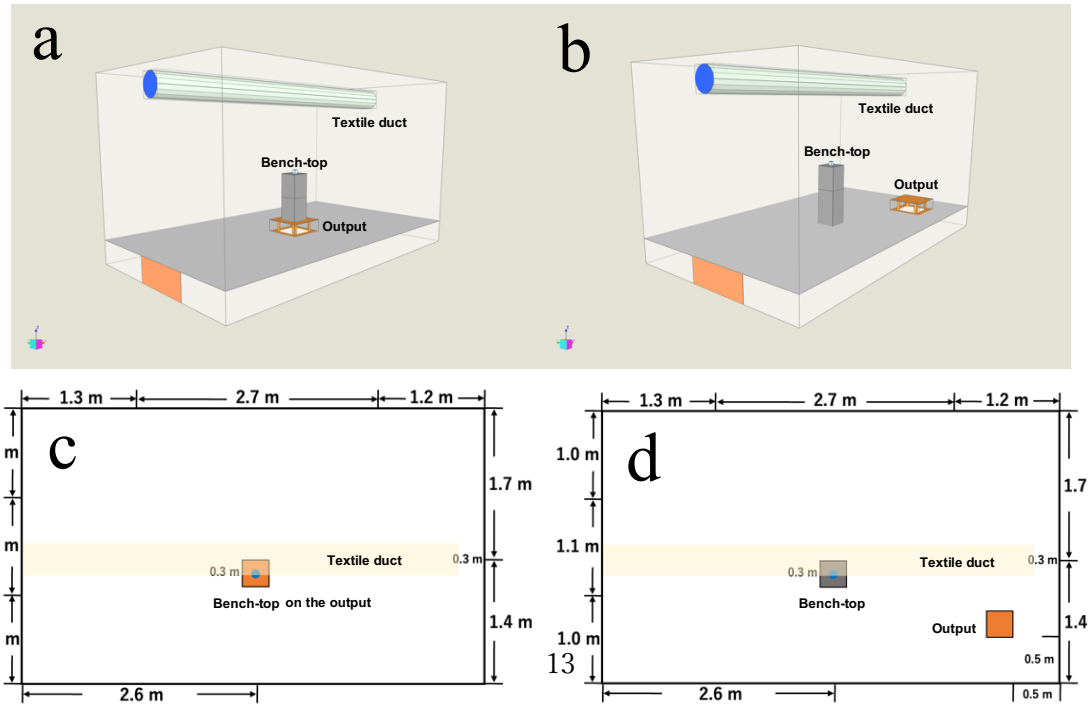
particularly in the region where pollutants congregated. This study provided substantial ramifications for the development of innovative downflow ventilation and implications for energy efficiency.

Chapter 2 Methodology

2.1 Geometry of Experimental Laboratory

This investigation was conducted in a full-scale experimental laboratory mock-up with dimensions of 2.7 m x 5.3 m x 3.0 m, as is depicted in Fig. 2.1 (a - f). The laboratory mock-up is equipped with a Heating, Ventilation and Air Conditioning (HAVC) system with the air flux regulating from 0 m^3/h to 2200 m^3/h. The supplied air to the chamber was from a textile duct featuring with air porous fabric (Fig. 2.2. (a)) where air can be delivered as is illustrated in Fig. 2.2. (b). The textile duct was implemented to distribute air in a manner that is consistent and slow in the context of somatosensory comfort and energy efficiency. The supplied air was set at 25°C and the air flux was set as 600 m^3/h, 1100 m^3/h and 2200 m^3/h, the corresponding face velocity, the rate of air movement at the face of the air filter, is 0.02 m/s, 0.04 m/s and 0.06 m/s.

The floor exhaust was an open cube with effective exhaust area of 1.0 m^2. The exhaust cube can be positioned anywhere on the detachable floor. The exhaust cube on the floor should be as close to the source of contamination as possible and not impede the experimenter's movement during laboratory operation. Consequently, two places were selected for this experiment: the center and the corner, which are often utilized to set up laboratory bench-ups and experimental equipment. The targeted chemical was put on the square bench with the height of 1.1 m and the width of 0.3 m.



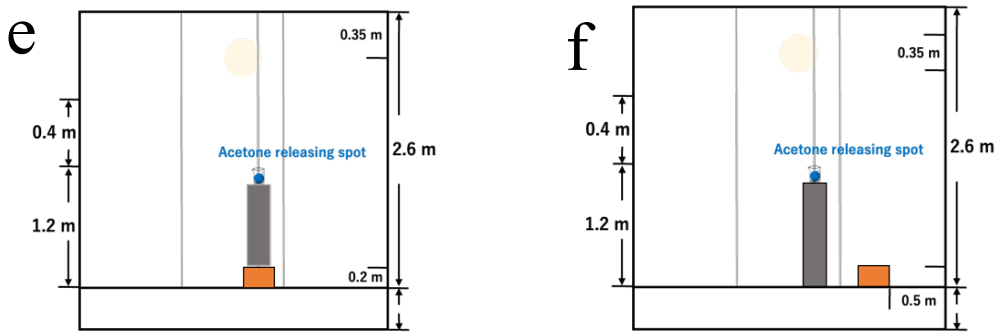


Fig. 2.1. Simulation (a, b), dimensions (c, d, e, f)
of full-scale experimental laboratory with two scenarios of ventilation

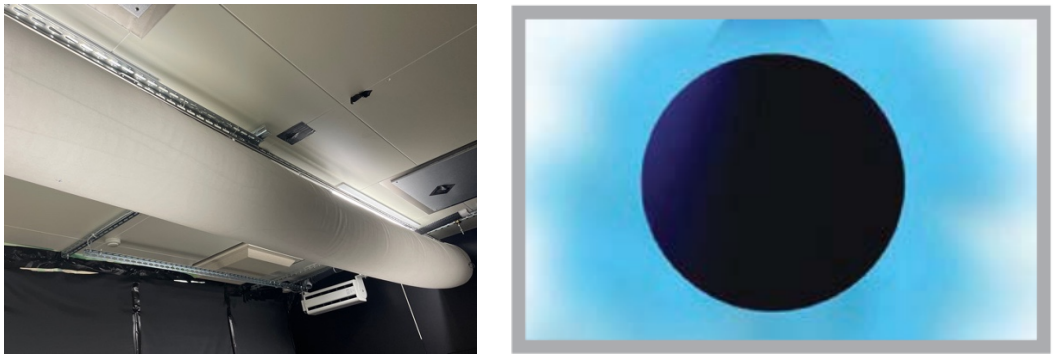


Fig. 2.2. Photo (a) and illustration (b) of the textile duct

2.2 Measurement Method of the Targeted chemical

The targeted chemical

This investigation measured the individual VOC under different ventilation flux and exhaust locations. Acetone was selected as the targeted individual VOCs based on the following reasons:

(i) Acetone is identified as one of the most abundant organic components from human metabolism and occupies 16.0% contributions to the total chemical species caused by human occupant emission as is depicted by Fig. 2.3[30].

(ii) Acetone, as well as benzene and toluene are the most common chemicals used in chemical laboratories.

(iii) The properties of acetone (Table. 2.1.) include low toxicity and effumability, making it possible to guarantee that the air pollutant concentration was well within the instrument's detection range and would not pose serious health risks to the researchers during short exposure.

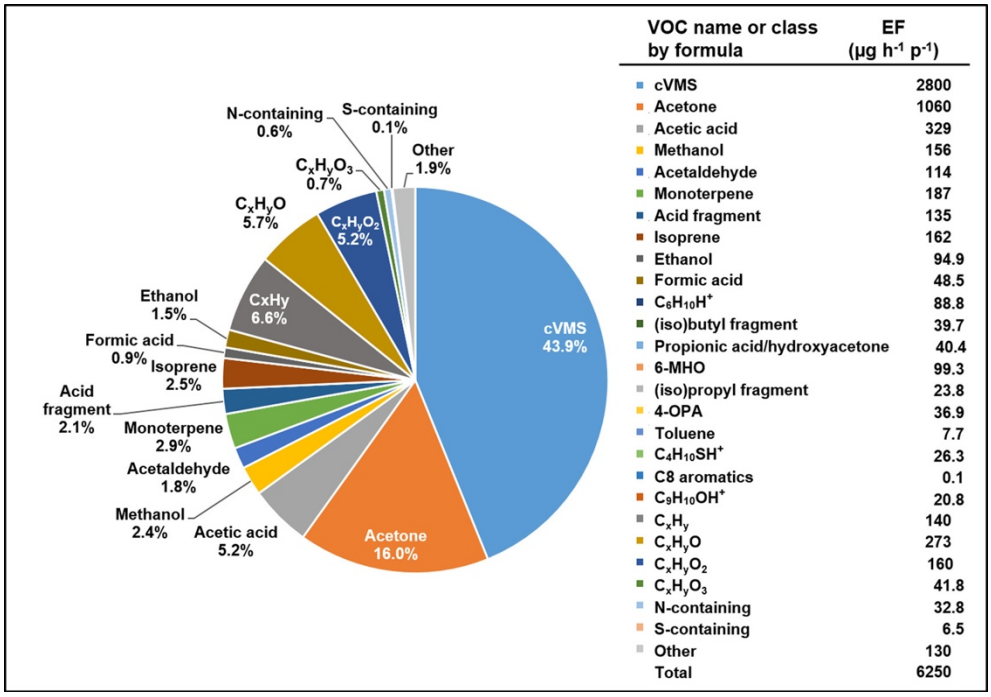


Fig. 2.3. Pie chart of contributions to the total chemical species caused by human occupant emission

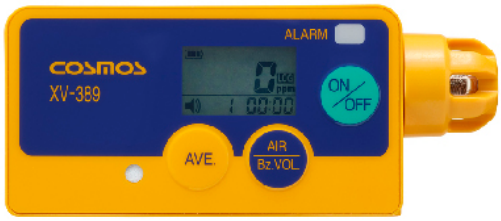


Fig. 2.4. The photo of the thermal-semiconductor-type detector utilized (COSMOS, XV-389)

Table 2.1

The properties of acetone (NIOSH AL3150000)

Molecular diffusion coefficient in air (m/s, 25°C)	**Vapor Pressure (mmHg, 25°C)**	**Experiment density (g/mL)**	**Vapor density**
1.24×10^{-5}	348.4 ± 0.1 mmHg at 25°C	0.791	2.0 (Air = 1)
Saturated concentration (mol/m^3)	**Limit values**	**Toxicity**	
12.30	TWA: 500 ppm (1200 mg/m^3) STEL: 750 ppm (1780 mg/m^3) Ceiling: 25 ppm	Eye and respiration irritation	

The release rate of acetone on the benchtop was calculated by Mazak (B.T.M) Formula.

$$G = (5.38 + 4.1u)\frac{p_v}{133.32}F\sqrt{M} \quad (1)$$

- G: the releasing rate of organic solvents (g/h)
- u: the wind speed (m/s)
- p_v: the saturated vapor pressure (Pa)
- F: the open area (m^2)
- M: the relative molecular mass

It is important to note that the density of acetone, which is twice than that of air. Gaseous contaminants are often regarded as passive gas, which means that the contaminant gas transport is primarily influenced by the bulk air movement and turbulent diffusion, and only marginally influenced by the contaminant density and molecular diffusion. However, some studies on gaseous contaminants found the vertical stratification concentration caused by density difference in low velocity ventilated areas.

There are other factors besides variation in density that go into determining whether or not the releasing acts as a dense gaseous pollution[31]. The initial airflow velocity, the releasing rate should also be considered to determine the dense gas dispersion. According to Britter, the effectively passive cases occur when

$$(g' \times q_v / D)^{1/3} U < 0.15 \quad (2)$$

- q_v: a continuous source of volume flow rate (m^3/s)
- g': source density difference, $g' = g[(\rho - \rho_a)/\rho_a]$; g: acceleration of gravity (m/s^2); ρ: the density of the released gas (kg/m^3); ρ_a: the density of the ambient air (kg/m^3).
- D: the source dimension (m).
- U: the ambient velocity (m/s).

Therefore, according to the equ. (2), the maximum ambient velocity can be calculated to serve as a criterion for the gas gravity effect.

$$U_{max} = (\frac{g q_v}{D})^{\frac{1}{3}} / 0.15 \quad (3)$$

In this study, 50 mL Acetone was placed in an 8-cm-diameter beaker to imitate a contamination source. The surface area of acetone at 25°C (300.15 K) was calculated to be 0.005 m^2. The acetone was detected by VOC detector (COSMOS, XV-389, Fig. 2.4.) with the detecting limitation of 0 – 500 ppm with ± 10% of full-scale. In order to detect the concentration of acetone in all areas of the laboratory, the beaker containing

acetone was left on the table so that a specific amount of acetone was present in the background concentration of the experimental laboratory, as was shown in the orange section in Fig. 2.5. After 40 minutes, the concentration of acetone at each measurement point attained a steady level of around 10 ppm and be easily detectable, and there were noticeable fluctuations and drops in concentration after activating the air exchange for 30 minutes, as was shown in the blue section in Fig. 2.5. The three shades of blue respectively represent three operation conditions of HAVC under 600 m^3/h, 1100 m^3/h and 2200 m^3/h expressed in Cube Meter per Hour (CMH).

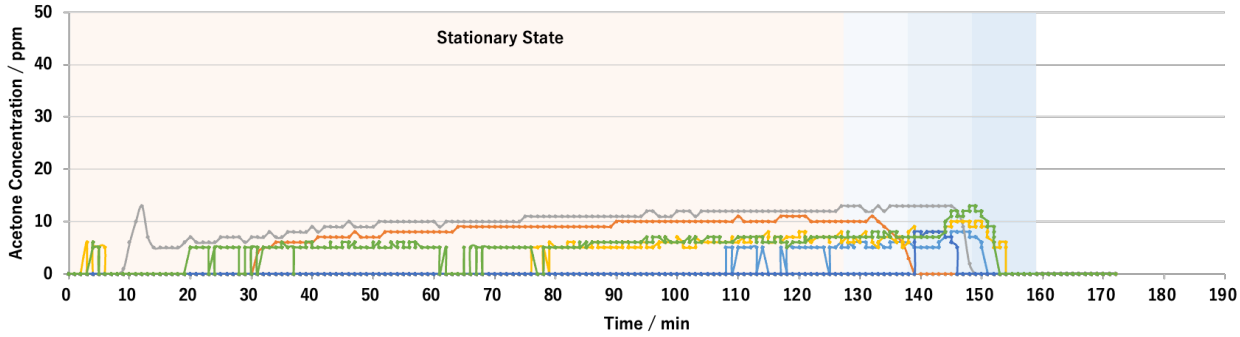
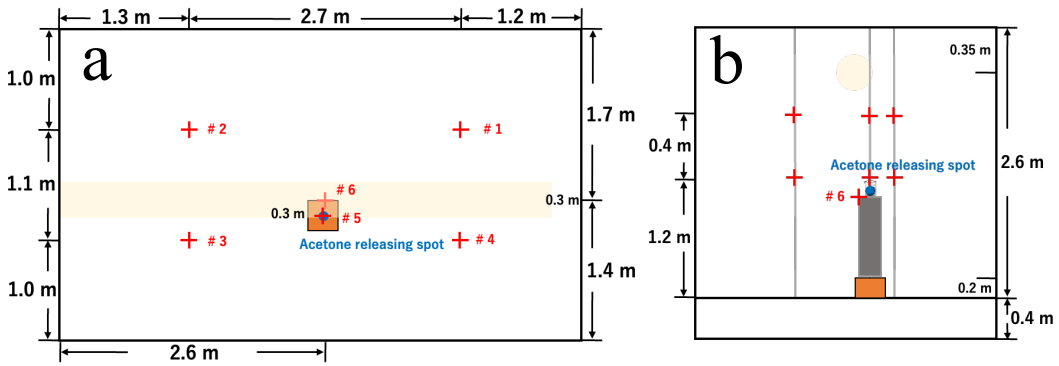


Fig. 2.5. The measured diffusion of acetone in the experimental laboratory

Detection location

As depicted in Fig. 2.6 (a, b), the acetone concentration was measured at five positions (detector #1 to #5) at different height (1.2 m and 1.6 m), and detector #6 was placed in the distance of 5 cm on the benchtop (Fig. 2.6 (c)).



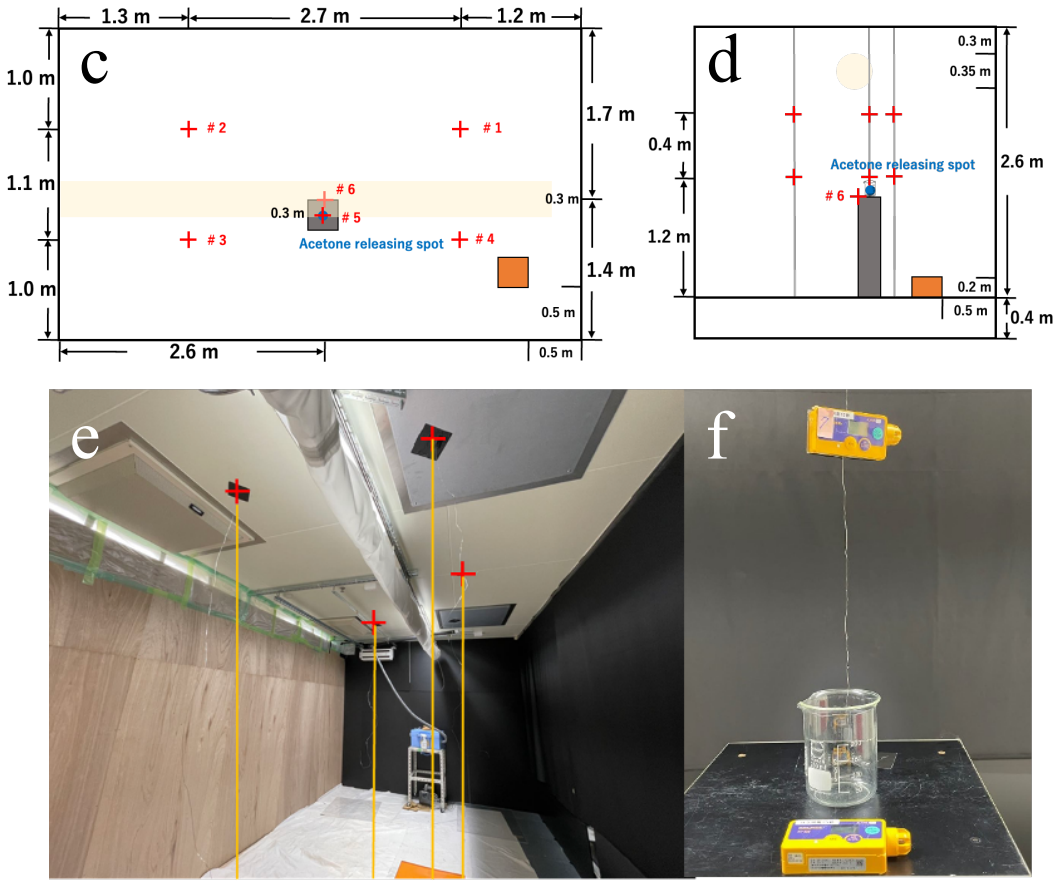


Fig. 2.6. Measurement locations: (a, b) horizontal and vertical locations under center scenario, (c, d) horizontal and vertical locations under corner scenario; photos (e, f) of the experimental laboratory and the detector in the vicinity of the beaker.

Observing the entire interior of the laboratory in a full scale was complicated, so this experiment concentrated on the part of the laboratory that was most important to us, namely the breathing zone. The height of the breathing zone was defined between 1.2 m to 1.6 m in this study. When workers in a laboratory are transferring or weighing solvents, their hands may come into touch with the benchtop, or they may remain in near vicinity to the area where the containers are kept. This poses a potential risk of skin contact or inhalation of the hazardous solvent. The test points (#1 - #4) away from the beaker were put uniformly at the corners around one meter away from the beaker because, based on the real laboratory indoor layout, these test sites are usually to be in the laboratory's corridor, which is where the laboratory staff breathes the most. Concerned about the influence of the contamination source to the surrounding air, two detectors (#5 and #6) were also placed beside and above contamination source as are depicted in the Fig. 2.6 (e, f).

As summarized in Table 2.2, this investigation conducted 12 cases of measurements to evaluate the influence of the ventilation rates and exhaust locations on the contaminant distribution in the laboratory. This investigation tested Cube Meter per Hour (CMH) at 600 m^3/h, 1100 m^3/h and 2200 m^3/h, the corresponding face velocity is 0.02 m/s, 0.04 m/s and 0.06 m/s under two exhaust locations (center and corner).

Table 2.2

Experimental cases studied in the point-wise measurement of acetone.

Case	CMH	Exhaust location	Detecting height (m)
1	600	center	1.2 (#1-#5) + #6 beside the beaker)
2	600	center	1.6 (#1-#5) + #6 beside the beaker)
3	1100	center	1.2 (#1-#5) + #6 beside the beaker)
4	1100	center	1.6 (#1-#5) + #6 beside the beaker)
5	2200	center	1.2 (#1-#5) + #6 beside the beaker)
6	2200	center	1.6 (#1-#5) + #6 beside the beaker)
7	600	corner	1.2 (#1-#5) + #6 beside the beaker)
8	600	corner	1.6 (#1-#5) + #6 beside the beaker)
9	1100	corner	1.2 (#1-#5) + #6 beside the beaker)
10	1100	corner	1.6 (#1-#5) + #6 beside the beaker)
11	2200	corner	1.2 (#1-#5) + #6 beside the beaker)
12	2200	corner	1.6 (#1-#5) + #6 beside the beaker)

2.3 Measurement Method of Airflow Field

Experimental observations and numerical simulations based on Computational Fluid Dynamics (CFD) are the two primary tools for analyzing the airflow inside laboratories[7]. The computational model is to be accepted if the numerical simulation results are validated by comparing them to experimental data. CFD models must be validated under physical conditions and environmental parameters that are as consistent as possible with the modeled conditions, particularly for unique environments such as in the laboratory ambient with complex geometry and multi-physical features that will jointly influence the local airflow pattern. Therefore, even though it is more expensive to conduct experimental measurements, it is necessary to conduct detailed experimental measurements of airflow organization, and the experimental data obtained serves as the foundation for future CFD numerical simulations, and pollutant propagation.

2.3.1 CFD

Numerical model

The CFD method was employed by using FlowDesigner 2022. k-ε two-equation models, which include the conventional k- ε model, the RNG k- ε model, and the Realizable k- ε model, are currently utilized to simulate the majority of indoor airflow turbulence models. This study employed the RNG k- ε model because, among these three frequently used k- ε models, the RNG k- ε model is suited for simulating interior airflow.

Boundary conditions

The air supply fixture is a duct comprised of seventeen air supply panels. The round tube has a diameter of 0.35 meters. The boundary condition for the duct is a uniform velocity normal to the boundary. The velocity of supply air varies among different cases, and the temperature is set as 25 ℃ in all cases. The supply inlet was “velocity inlet” and the exhaust was set as a “mass flow outlet”. The unheated contamination source was defined as a “mass flow inlet”.

2.3.2 PIV

Airflow field visualization and measurement is crucial for quantitatively comprehending general or local airflow velocity, direction, turbulent properties and other airflow field information. Compared to conventional interventional, single-point velocimetry equipment, PIV, or particle image velocimetry, has the advantage of obtaining instantaneous, full-field flow information without altering the flow field (e.g., thermal spheres, hot-wire anemometers, ultrasonic anemometers)[32]. PIV has evolved into one of the most crucial measurement techniques in experimental fluid dynamics over the last decade supported by the quick growth of camera imaging, laser technology, data transmission and storage. A typical 2D-PIV measurement system consists of five components as is shown in Fig. 2.7.: illumination system, image recording devices, the generator of tracer particles, the synchronizer and the computer for analysis. The analysis procedures are represented in Fig. 2.8: The image recording device (usually is CCD camera, with a charged-couple device to capture optical signals with high-sensitivity) record the laser-illuminated particle images under the control of the synchronizer. And these images of dispersed particles are then sent to a computer. Using the PIV processing software on the computer, the instantaneous airflow field will be calculated by the short interval $\triangle t$, and the displacement of tracer particles $\triangle x$.

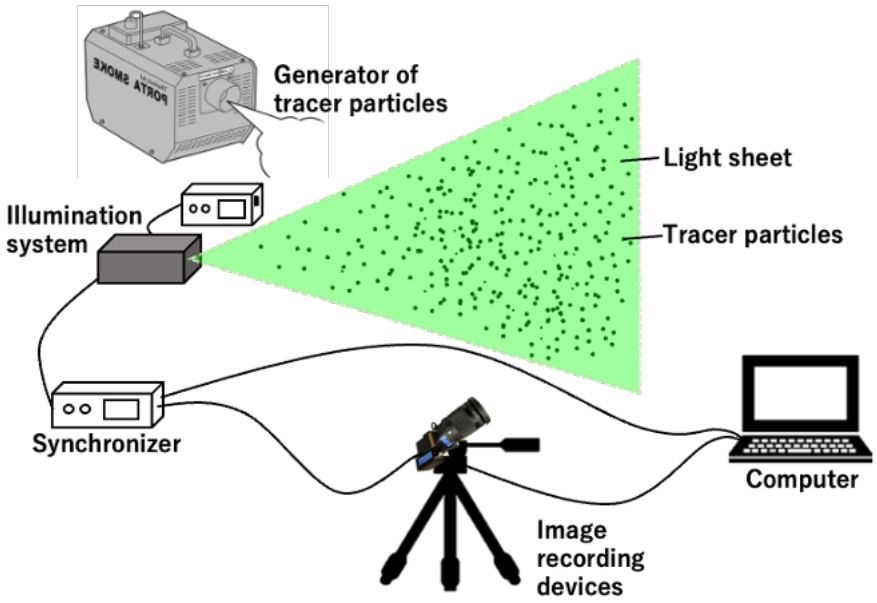


Fig. 2.7. Schematic of a 2D-PIV measurement system

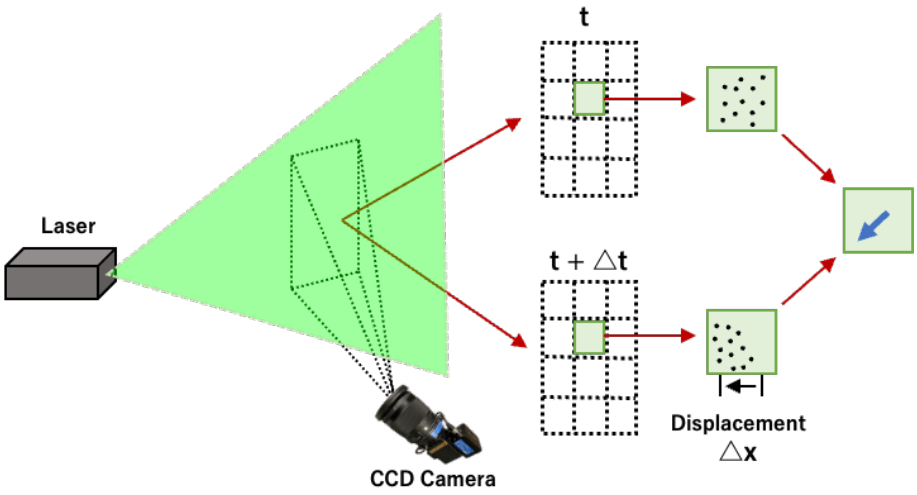


Fig. 2.8. Schematic of the PIV principle for airflow field calculation

It is important to note that the selection and delivery of tracer particles have a substantial effect on the measurement findings since the PIV system is intended to characterize the flow field by detecting the flow of tracer particles. The tracer particles must have the following properties: (i) The tracer particles must follow the fluid flow well; (ii) The particle size and concentration of the tracer particles must be appropriate; (iii) There must be no interaction between tracer particles; and (iv) The tracer particles must have good light scattering properties. The objective of continuous PIV measurements with large sampling volumes is to create a steady and uniform dispersion of tracer particles in sufficient concentration over an extended period. In this experiment, the large-scale non-constant flow phenomenon was investigated, and the tracer particles required for PIV measurements must be uniformly disseminated in the experimental laboratory in sufficient concentration.

2.3.2 Experiment setup of PIV

To scatter tracer particles uniformly throughout the chamber in this study, the tracer particles were fed in advance at the upstream region above the overall air supply duct through a tube, and then mixed with supply air in the chamber. This investigation utilized stage oil generator using the thermogenesis method to generate ester aerosols (mixture of propylene glycol, tripropylene glycol and 1,3-Butanediol) that are particularly difficult to volatilize in air and are suspended in the air. The actual experimental setup is depicted in Fig. 2.9. Table 2.3 provides a summary of the remaining significant PIV measurement parameters. For the statistical analysis, 360 uncorrelated instantaneous flow fields with a sample frequency of 3 Hz were

employed to produce time-independent flow field data. The post-processing software and velocity distributions were obtained using the software FlowExpert v1.3.3.

Table 2.3

Key parameters and settings of the PIV experiment.

Camera	Camera type	Sony ZEISS
	Lens	Vario-Sonnar F1.8
	Resolution	3840 pixel × 2160 pixel
	Frame rate	960 fps
Laser	Laser source	Diode-Pumped Solid State (DPSS) green laser
Tracing particles	Smoke generator	Dainichi (PS-2007) PORTA SMOKE
	Particle type	aerosols of propylene glycol, tripropylene glycol and 1,3-Butanediol
Tracing particles	Median particle diameter	$\approx 10\ \mu m$
Algorithm	Interrogation window	32 pixel × 32 pixel
Field of view	Section	0.6 m × 0.3 m

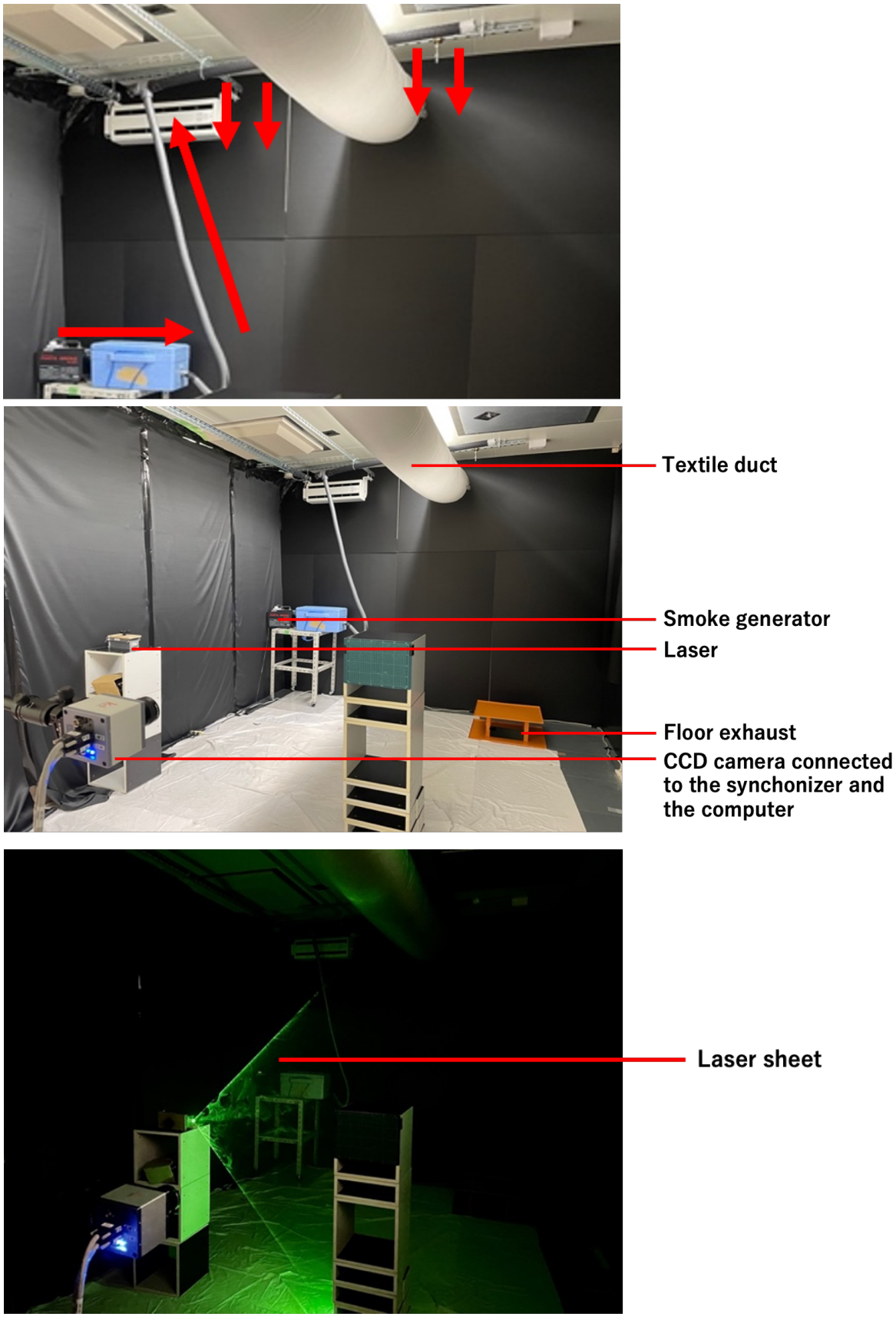


Fig. 2.9. Photos of the PIV experimental setup

Table 2.4

Experimental cases studied in PIV experiment.

Case	CMH	Exhaust location	Detecting section
1	2200	center	Section 1
2	2200	corner	Section 1

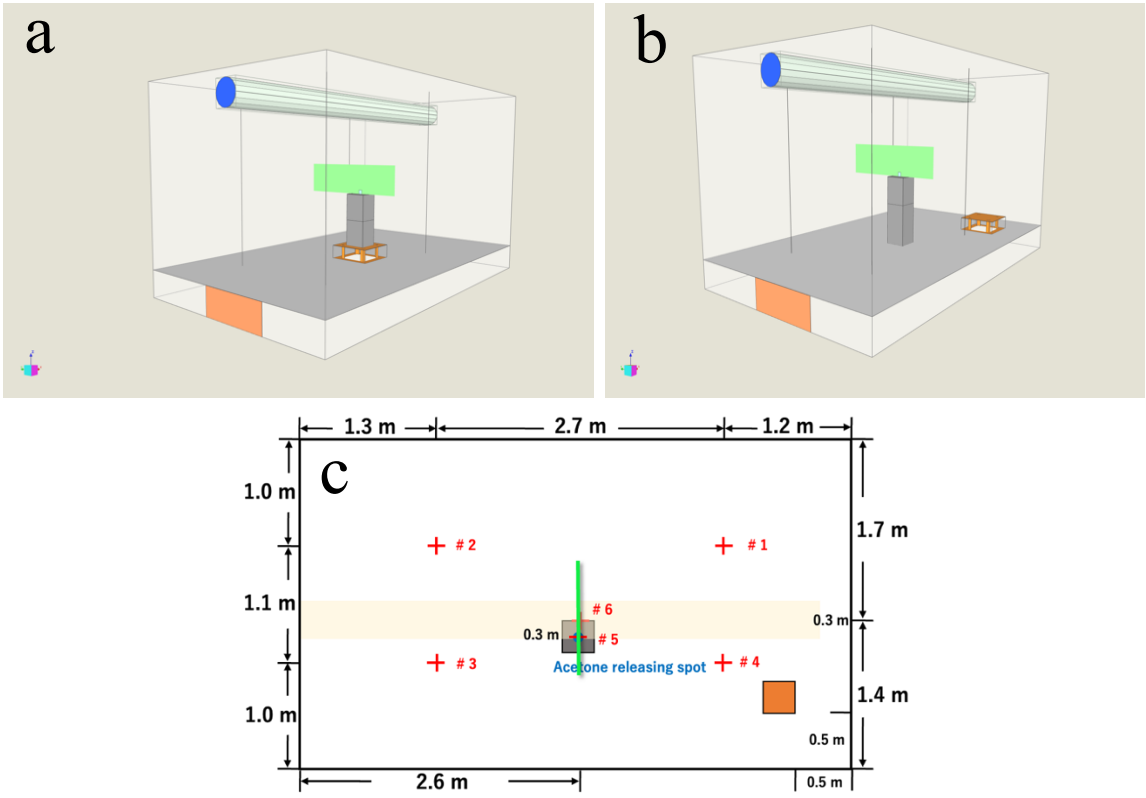


Fig. 2.10. Illustration of the PIV experiment cases: illustration of section 1 in the experimental laboratory.

Chapter 3 Results

This investigation evaluated the acetone distribution and airflow field to assess the ventilation performance of a novel downflow ventilation system. The experiment particularly focused on local feature of the contaminant distribution and airflow field within breathing zone and the vicinity of the contamination source. 12 cases of acetone concentration in 6 spots were collected and 12 cases of the local features of the airflow distribution were visualized under different factors, including ventilation rates and exhaust location.

The experimental results are presented in two parts, the first of which is a comparison of the concentrations in the breathing zone (BZ), i.e., the data for detection spots from #1 to #4 in the height of 1.2 m and 1.6 m. The second part consists of the results for the vicinity of the contamination source (CS), i.e. detection spots #5 (in the height of 1.2 m and 1.6 m) and #6. The detection spots are illustrated in the Fig. 3.1.

These two components are essential. Due to the fact that the four spots in the breathing zone are located in the laboratory's corridor, this depicts the pollution status in the breathing zone to which individuals are exposed when moving in the laboratory. The second part is the concentration distribution at the source of contamination, which corresponds to the contamination in the breathing zone and around the desk when the experimenter is conducting laboratory-scale activities in close proximity to the hazardous chemical.

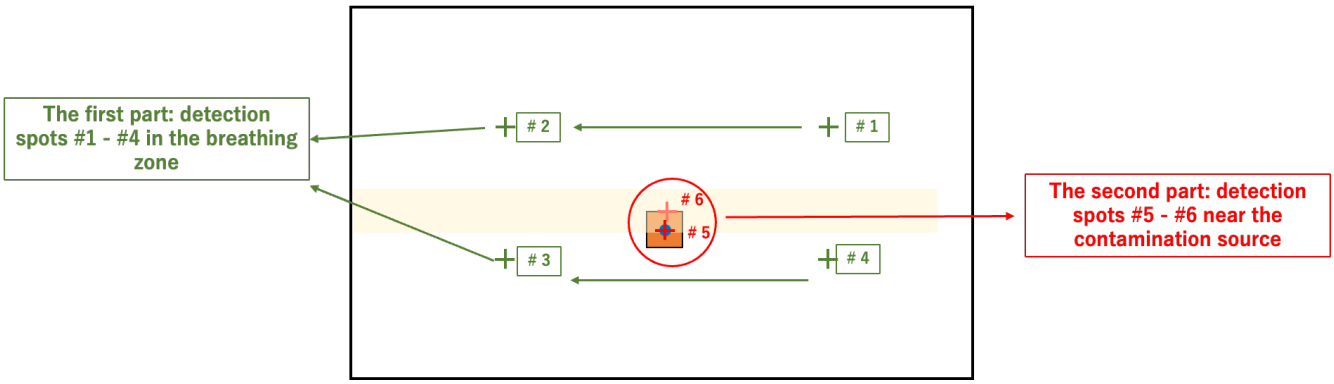


Fig. 3.1. Illustration of detection spots for two parts

3.1 Acetone Distributions with Different Ventilation Rates

3.1.1 The first part: acetone distributions in the breathing zone

Fig. 3.2. compares the concentration of acetone at three different ventilation rates (600 CMH, 1100 CMH, and 2200 CMH) in the height of 1.2 m and 1.6 m (case #1 - #6). During the first 40 minutes, the concentration of acetone in four detecting points in the breathing zone of the experimental chamber reached around 10 ppm. During the operation of ventilation system, as was highlighted in the red square, the acetone in the breathing zone could be removed within 10 minutes. Fig. 3.3. compares the time-weighted average (from the 40th min to the 70th min) of acetone concentration during the operation of ventilation systems at different rates. The average of acetone concentration in the height of 1.2 m was marginally higher than that in the height of 1.6 m. However, with the ventilation rates increasing from 600 CMH to 1100 CMH, there was a slight increase in the average contaminant concentration. A further increase of ventilation rate from 1100 CMH to 2200 CMH could reduce the average contaminant concentration.

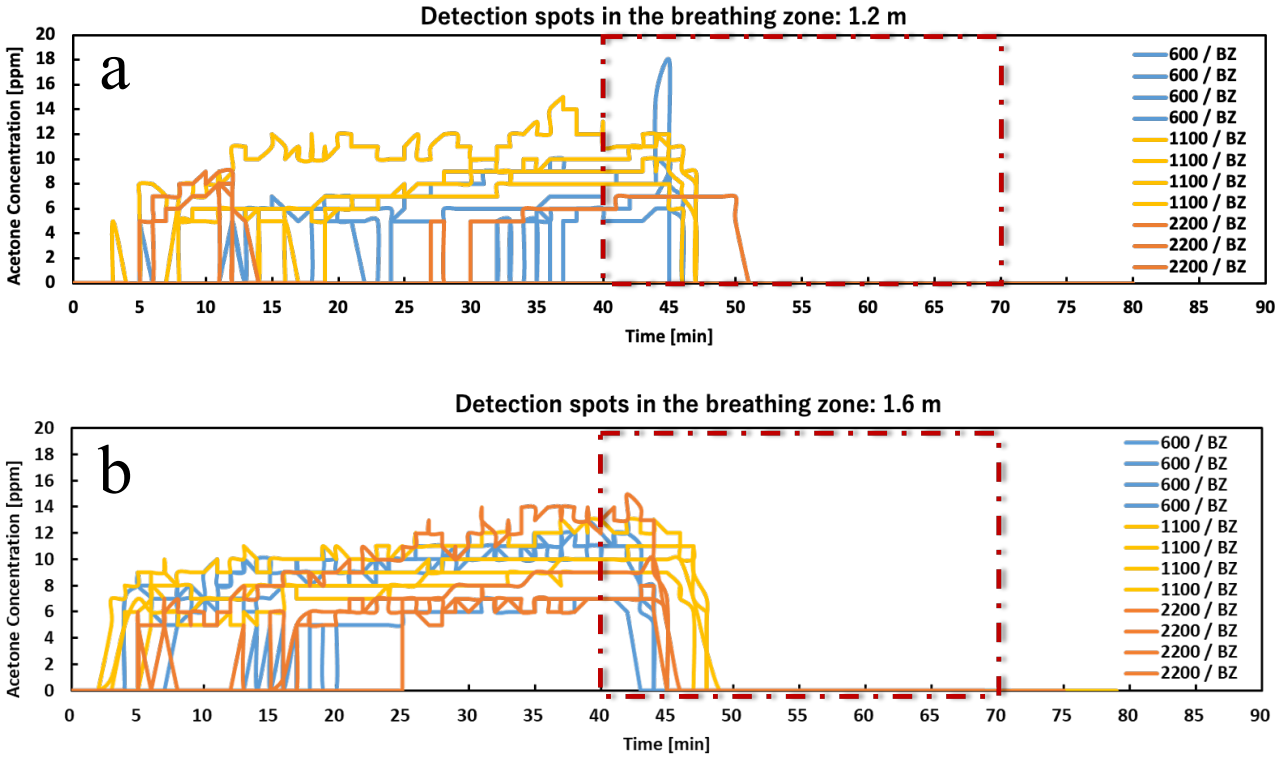


Fig. 3.2. Concentration of acetone in the breathing zone at different ventilation rates: (a) in the height of 1.2 m; (b) in the height of 1.6 m.

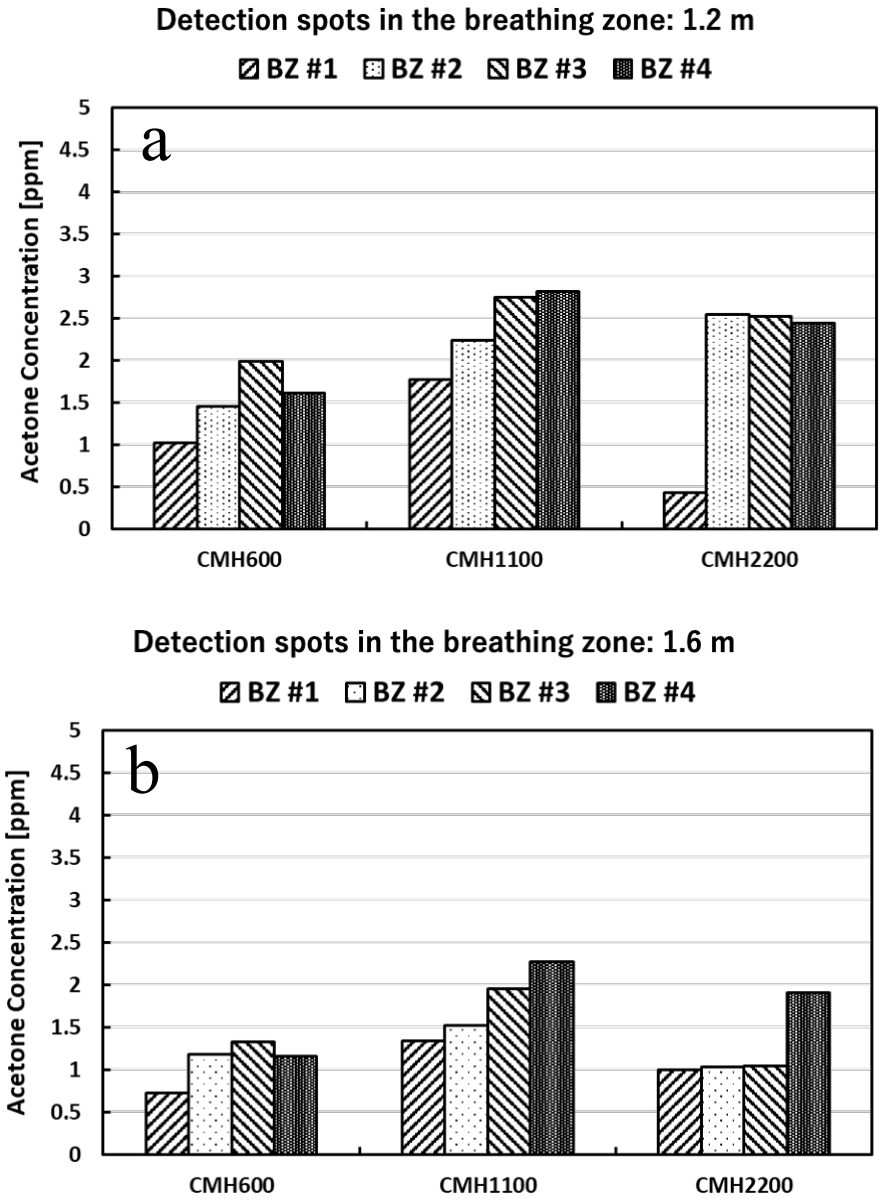


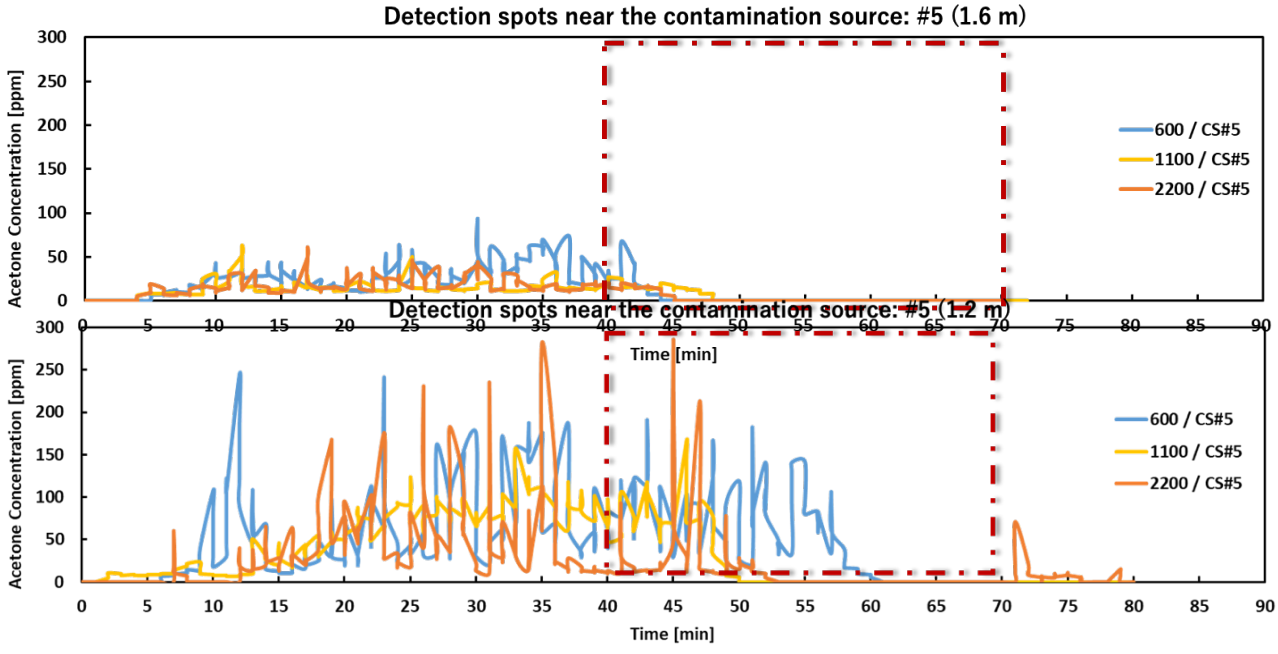
Fig. 3.3. Time-weighted average (from the 40th min to the 70th min) of the concentration of acetone in breathing zone at different ventilation rates: (a) in the height of 1.2 m; (b) in the height of 1.6 m.

3.1.2 The second part: acetone distributions near the contamination source

Fig. 3.4. compares the concentration of acetone at three different ventilation rates (600 CMH, 1100 CMH, and 2200 CMH) near the contamination source. In the detecting spots in the height of 1.6 m (Fig. 3.4. (a)), which is 0.42 m directly above the beaker with acetone, the acetone could be eliminated within 10 minutes. However, as is depicted in the Fig. 3.4. (b), the contamination concentration in the height of 1.2 m, which is 0.02 m directly above the beaker, the acetone concentration was much

higher than that in the height of 1.6 m, and took longer time to be eliminated. Under the ventilation rates of 600 CMH, 1100 CMH, and 2200 CMH, the eliminating time were 20 minutes, 15 minutes, and 10 minutes accordingly. Fig. 3.4. (b) depicts the acetone concentration beside the beaker on the benchtop. It reveals that the three ventilation rates could not effectively eliminated the acetone on the benchtop. The acetone concentration fluctuated and exceeded the detection limit during the operation of ventilation system. This reveals that in a low-speed laboratory airflow setting, large quantities of chemicals will be accumulated on the benchtop when the experimenter is dealing with chemicals that are heavier than air, and it is difficult to remove this accumulation with low-speed air exchange even directly under the ventilation duct. In such a scenario, the experimenter will be exposed to more risks as a result of changes in the organization of airflow caused by human respiration, air disturbance caused by hand movement, and the stacking of tabletop objects.

Fig. 3.5. compares the time-weighted average (from the 40th min to the 70th min) of acetone concentration in the three detecting spots near the contamination source at different ventilation rates. The same trend could be found in three detecting spots. The average acetone concentration decreased slightly with the ventilation rate increasing from 600 CMH to 2200 CMH. However, even with the ventilation rate in the 2200 CMH, it was difficult to eliminate the acetone accumulation on the benchtop. The time-weight average reached 220 ppm in 30 minutes during the operation of ventilation system, and it should be noted that the actual average was higher because the acetone concentration surpassed the detection limit multiple times.



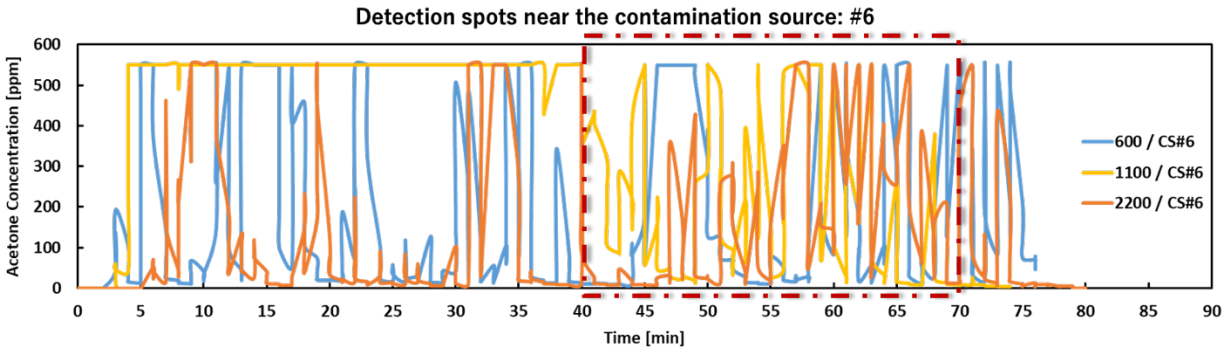


Fig. 3.4. Concentration of acetone near the contamination source at different ventilation rates: (a) Detecting spot #5 (1.6 m); (b) Detecting spot #5 (1.2 m); (c) Detecting spot #6 (beside the beaker)

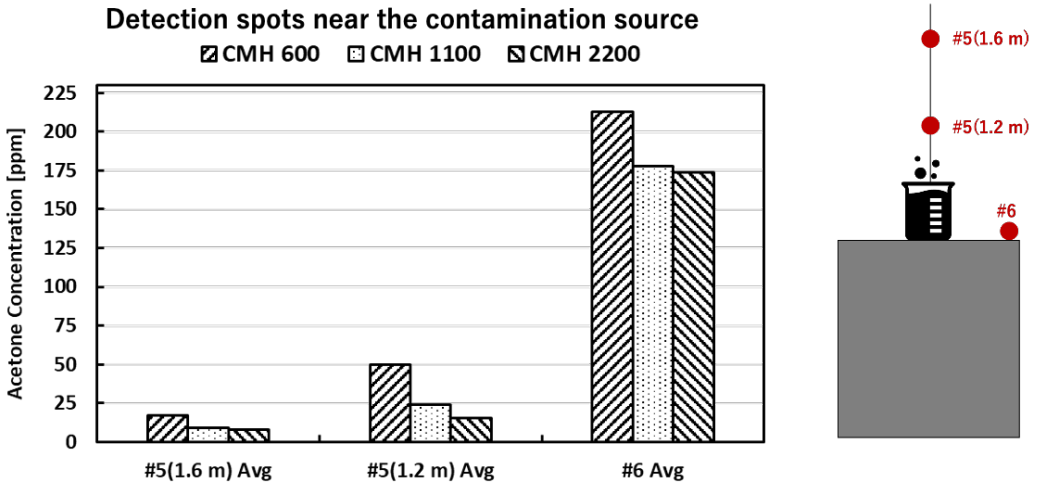


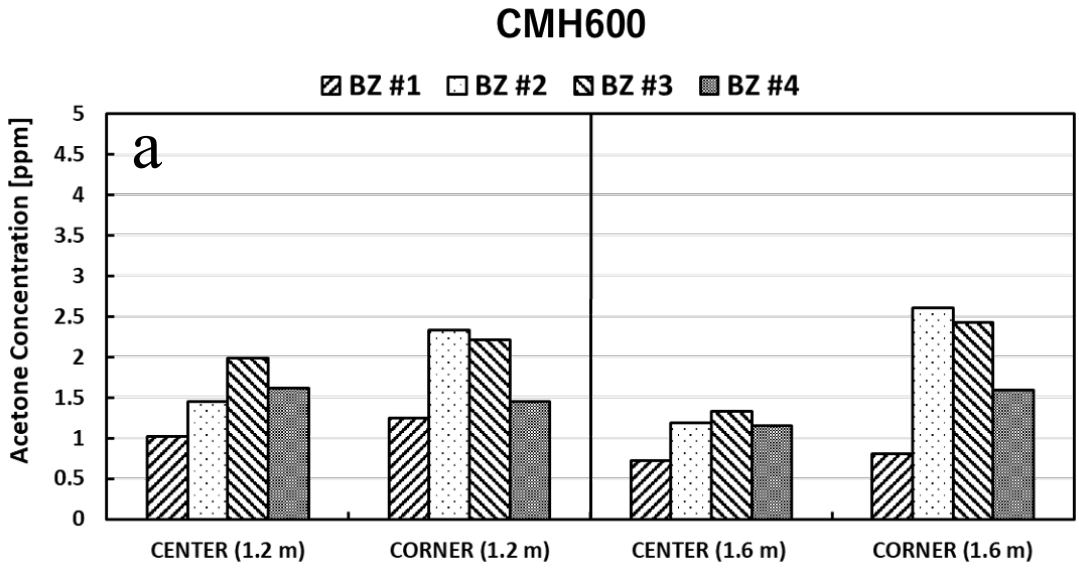
Fig. 3.5. Time-weighted average (from the 40th min to the 70th min) of the concentration of acetone in breathing zone at different ventilation rates

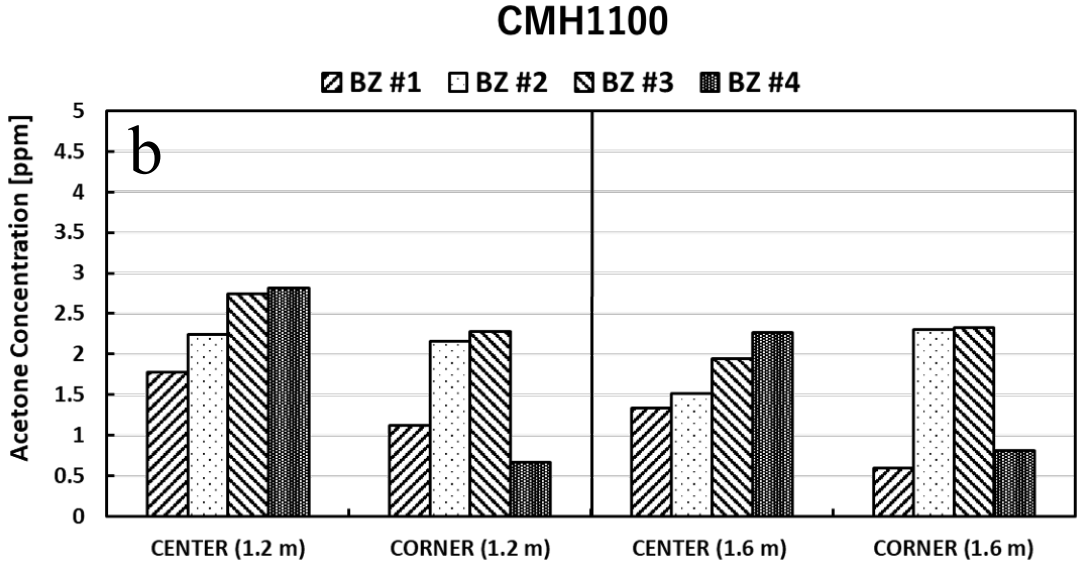
3.2 Acetone Distributions with Different Exhaust Locations

3.2.1 The first part: acetone distributions in the breathing zone

Fig. 3.6. compares the concentration of acetone at different exhaust locations (center and corner) in the breathing zone with fixed ventilation rates (CMH600, CMH1100, CMH2200). The time-weighted average (from the 40th min to the 70th min) concentration of acetone in the breathing zone was practically identical ranging from 0.5 ppm to 2.5 ppm. As aforementioned in Section 3.1.1, at all three ventilation rates, the acetone could be effectively removed from breathing zone within 10

minutes. Therefore, both ventilation rates and exhaust locations, in the scenario of low-speed ventilation, did not have much effect in the breathing zone of the corridor.





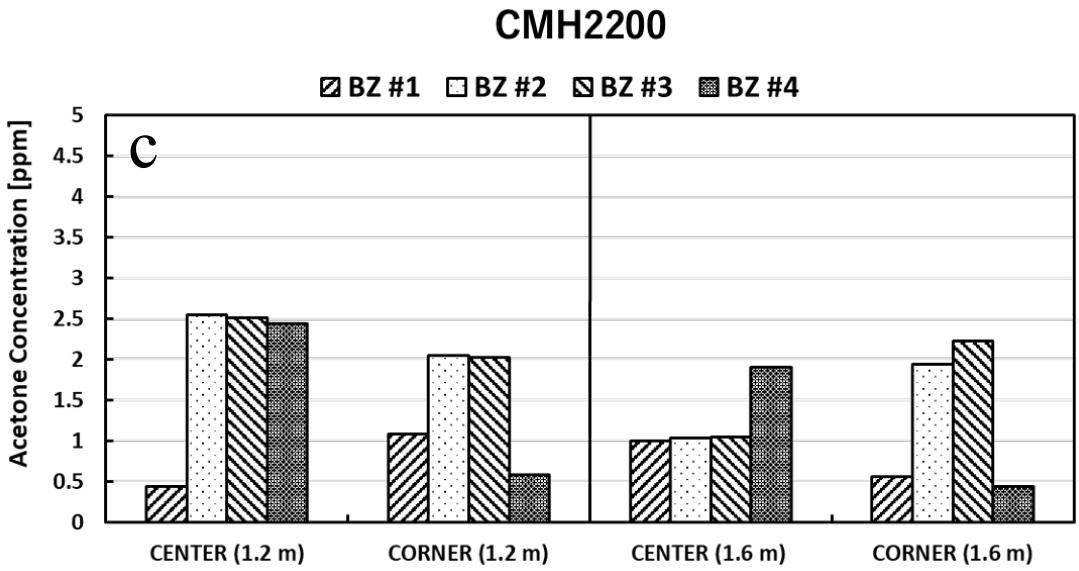
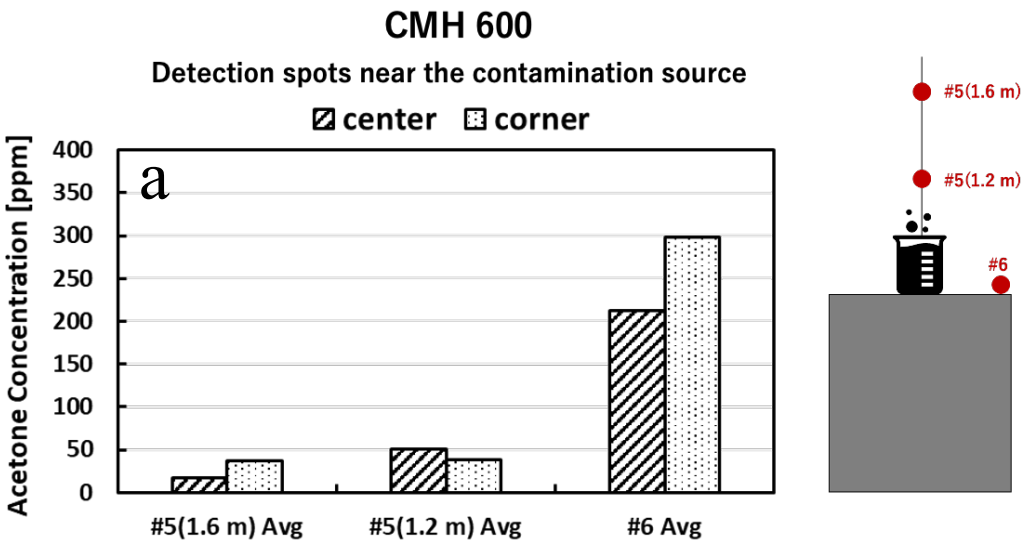


Fig. 3.5. Time-weighted average (from the 40th min to the 70th min) of the concentration of acetone in the breathing zone with fixed ventilation rate: (a) CMH600; (b) CMH1100; (c) CMH2200.

3.2.1 The second part: acetone distributions near the contamination source

Fig. 3.7. compares the concentration of acetone at different exhaust locations (center and corner) near the contamination source with fixed ventilation rates (600 CMH, 1100 CMH, 2200 CMH).



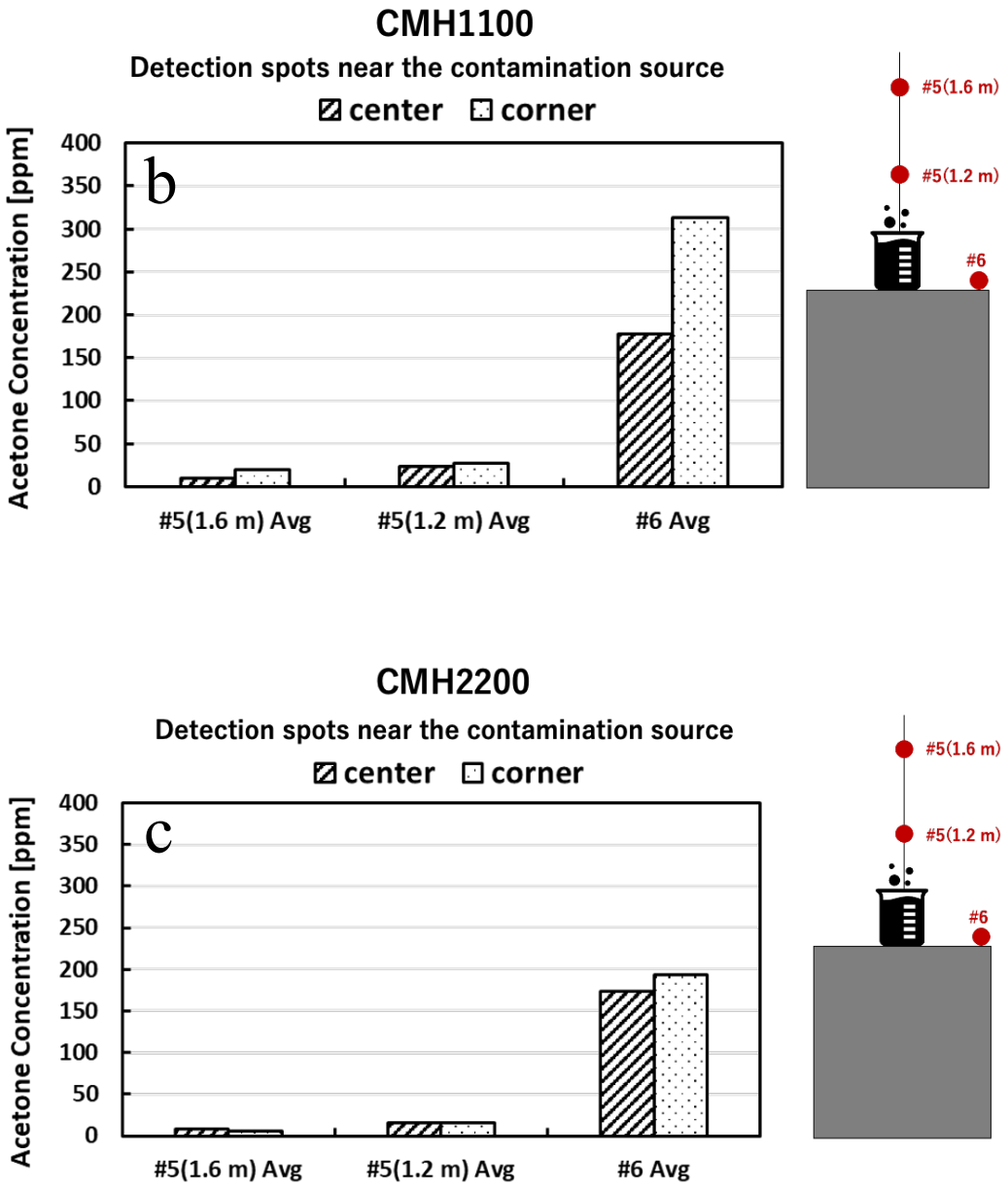


Fig. 3.7. Time-weighted average (from the 40th min to the 70th min) of the concentration of acetone near the contamination source with fixed ventilation rate: (a) CMH600; (b) CMH1100; (c) CMH2200.

3.3 CFD Results under Different Exhaust Locations

The CFD simulated the diffusion process of acetone under different exhaust location. To obtain the transient acetone concentration distribution during the diffusion process, transient simulation of the process was required. The initial conditions comprised the location of the source, the velocity of the released acetone, physical properties of

acetone, and the release time. The configuration of CFD cases is described in Table 3.1.

Table 3.1

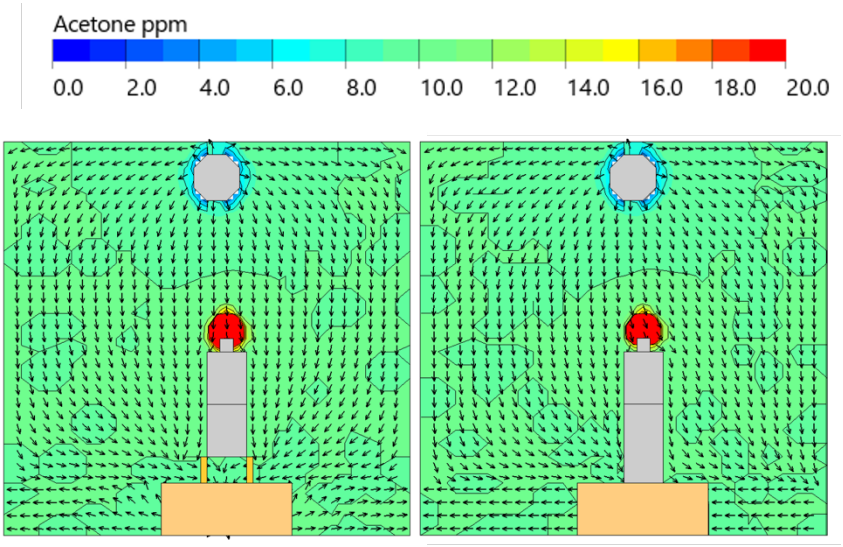
The configuration of in simulations

Case No.	CMH	Exhaust location	Releasing duration	Acetone background concentration
1	600	center	3 min	10 ppm
2	600	corner	3 min	10 ppm

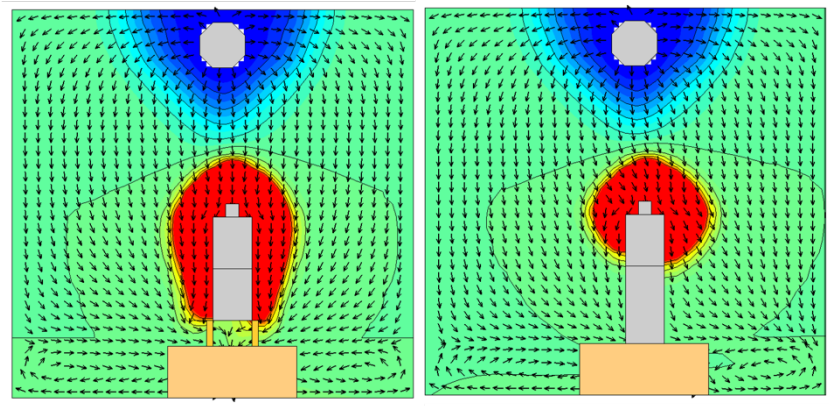
The acetone concentration distributions of the indoor pollution source were obtained for 1 s, 10 s, 30 s, 60 s, 200 s, 300 s, 400 s, 500 s and up to 600 s. Fig. 3.7. and Fig. 3.8. illustrated the temporal distribution of acetone concentration in the x = 2.46 m plane and y = 1.426 m plane. When there was an indoor pollutant release for 180 s, the transient simulation provided a comprehensive depiction of the acetone diffusion process under different exhaust locations. As seen in the Fig. 3.8. and Fig. 3.9. below, before 180 s, the concentration of acetone at the commencement of a release was primarily near the source, indicating that the source's boundary conditions dominated the concentration distribution during this brief period, while airflow played a little effect.

It was also evident that, after 200 s, acetone began to diffuse across the room, showing that the flow field was beginning to play a significant impact. And it could be observed that, in the center scenario, the acetone directly descended and flowed to the exhaust. Comparing to the corner scenario, it had the advantage of short path thus eliminating the acetone around the contamination source more quickly, at 500 s. For the acetone in the breathing zone, exhaust location did not have much effect, and this was consistent with the measurement results aforementioned.

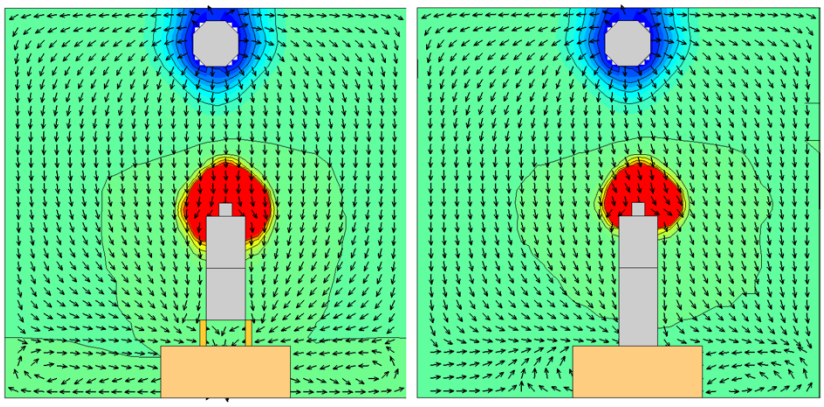
In addition, it is important to note that pollutants on the benchtop were released for 180 s and ceased to be released after 180 s. During the first 180 s, the acetone concentration on the tabletop was maintained at a high level due to the gravity effect of the acetone and the top-down wind, which was consistent with the above experimental results. After 180 seconds, the acetone was no longer released, and the acetone on the benchtop rapidly eliminated to the outlet, either to the center exhaust or corner exhaust.



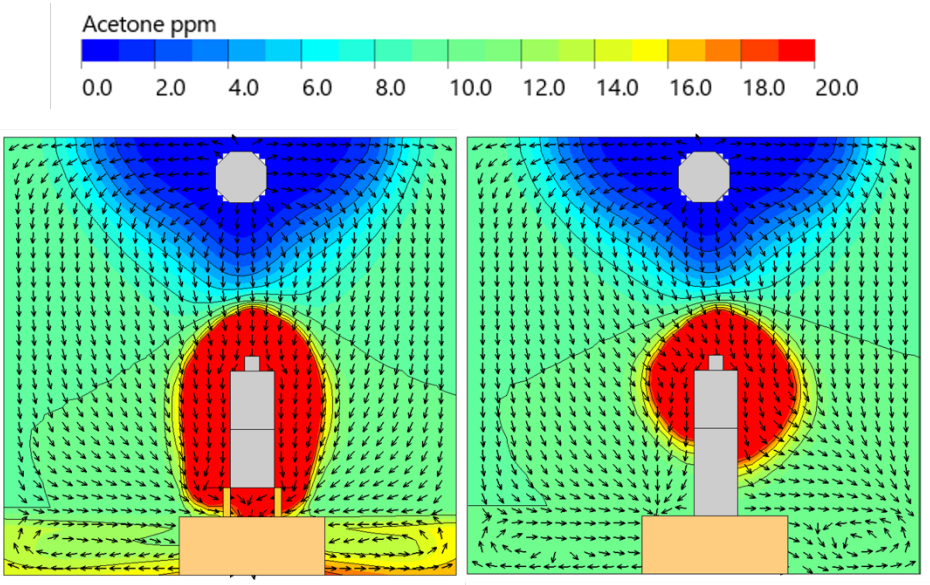
1 s (left: center; right: corner)



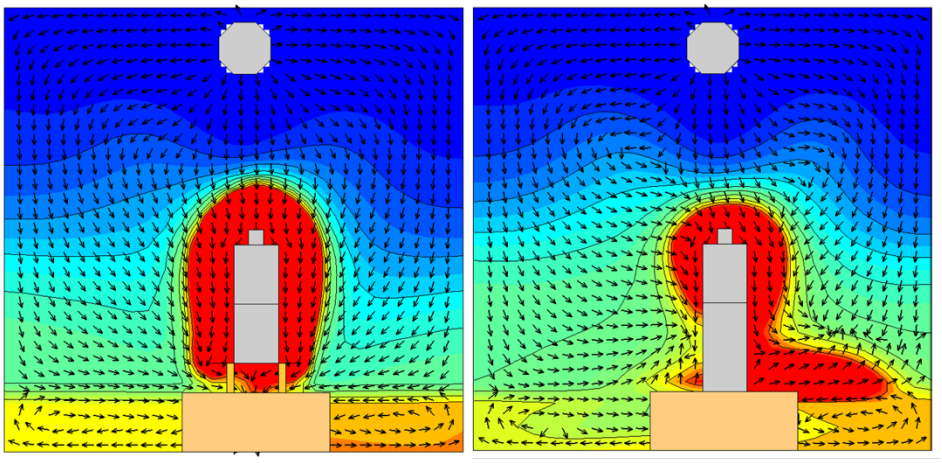
10s (left: center; right: corner)



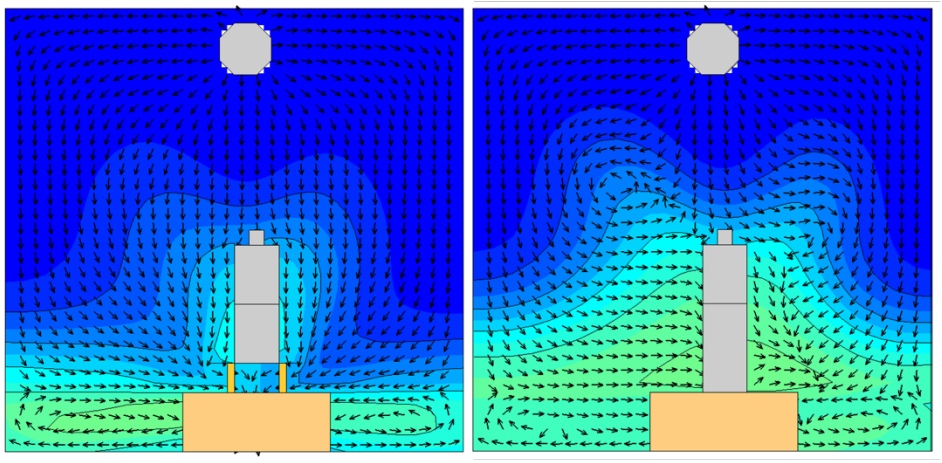
30 s (left: center; right: corner)



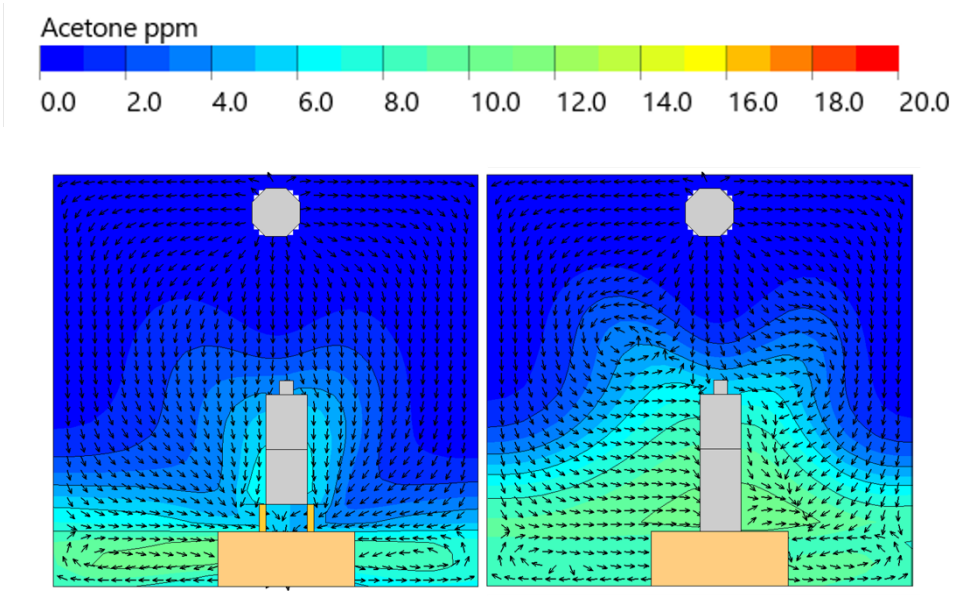
60s (left: center; right: corner)



200 s (left: center; right: corner)



300 s (left: center; right: corner)

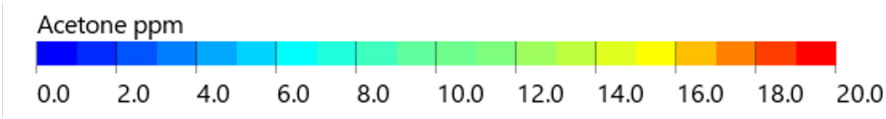


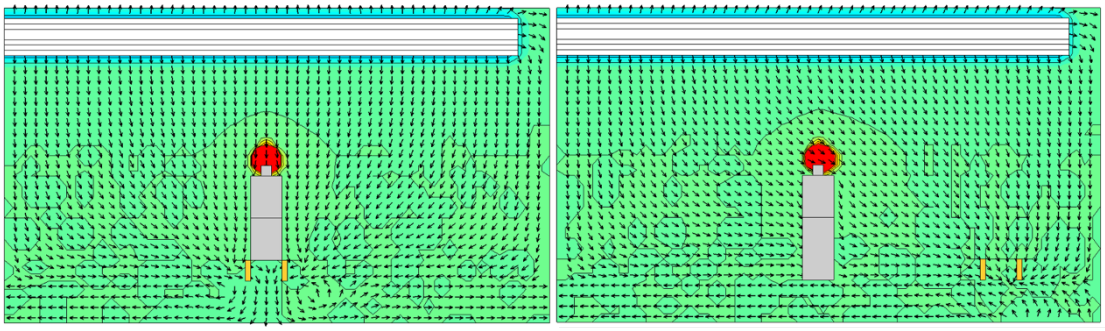
400 s (left: center; right: corner)

500 s (left: center; right: corner)

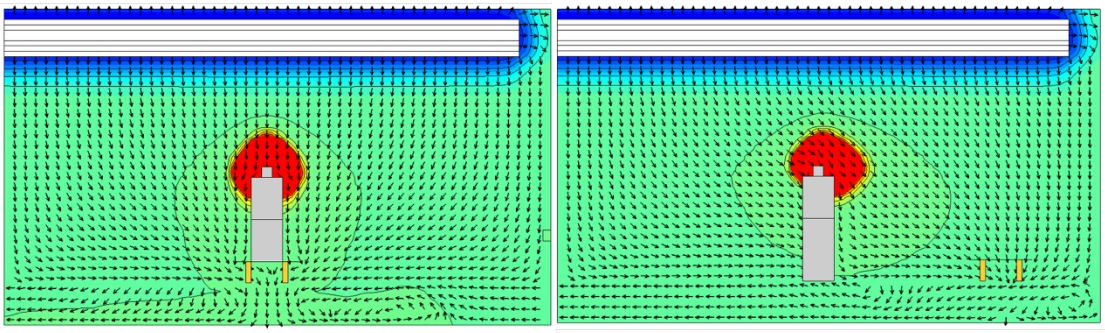
600 s (left: center; right: corner)

Fig. 3.8. Cloud map of acetone diffusion process (x = 2.46 m)

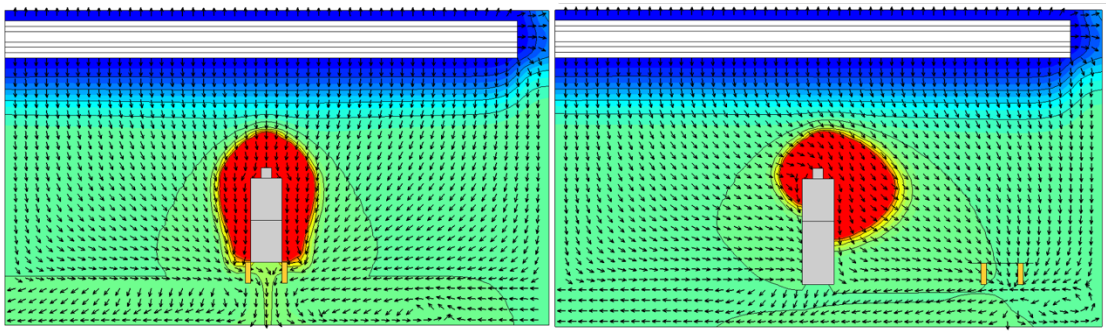




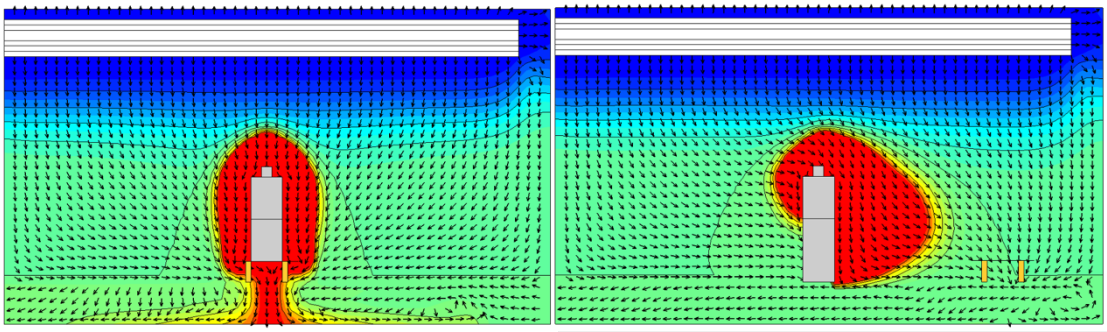
1 s (left: center; right: corner)



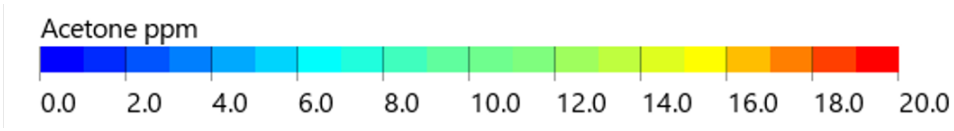
10 s (left: center; right: corner)

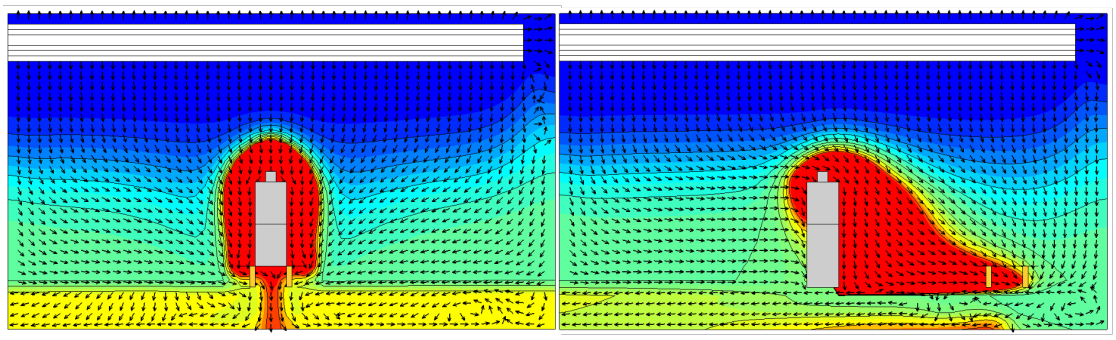


30 s (left: center; right: corner)

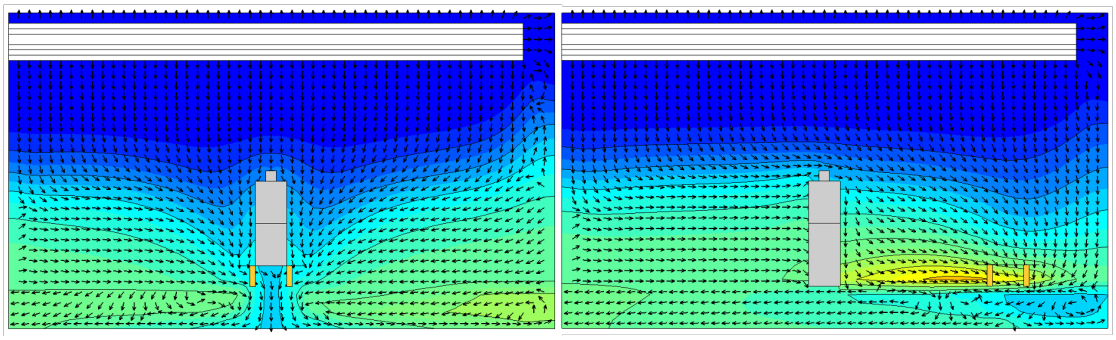


60 s (left: center; right: corner)

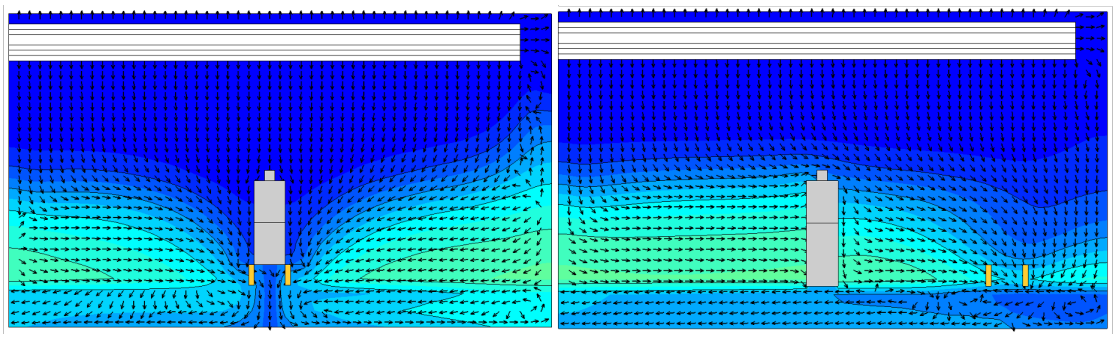




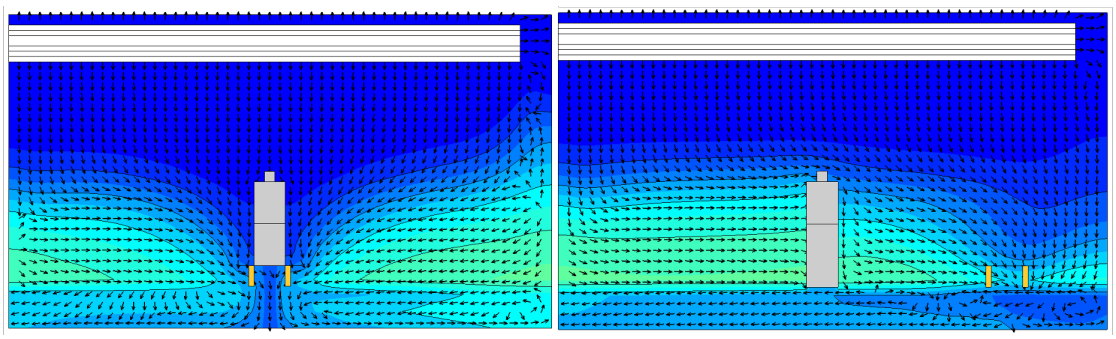
200 s (left: center; right: corner)



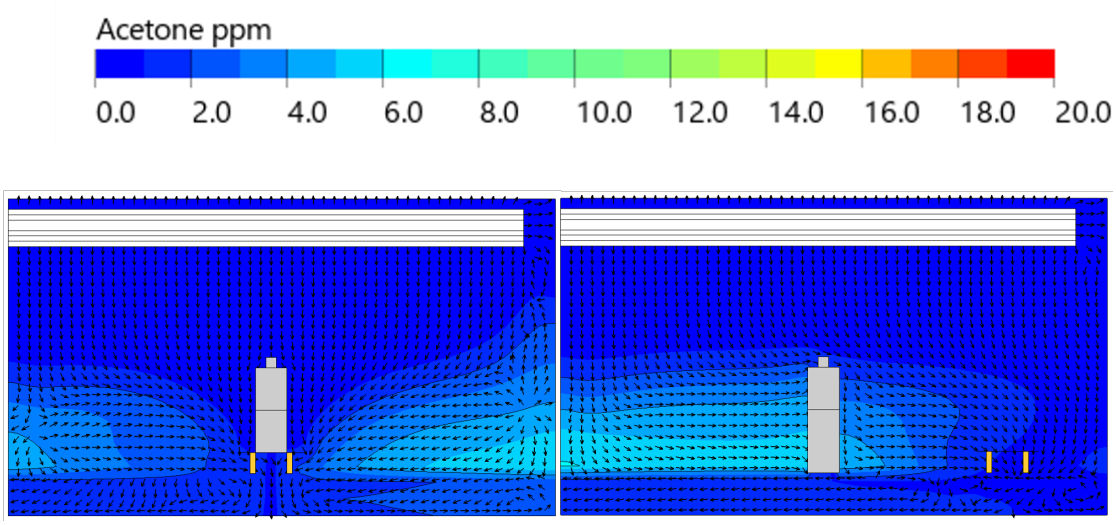
300 s (left: center; right: corner)



400 s (left: center; right: corner)



500 s (left: center; right: corner)



600 s (left: center; right: corner)

Fig. 3.9. Cloud map of acetone diffusion process (y = 1.426 m) under different exhaust locations (left column: center; right column: corner)

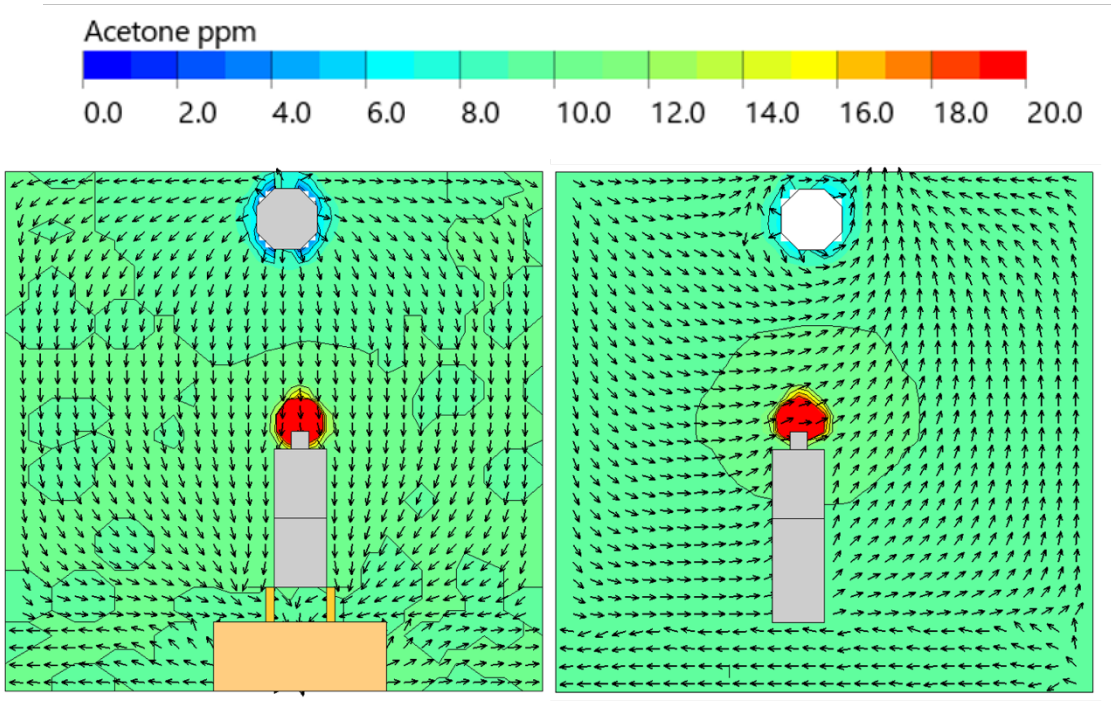
The comparison between downflow ventilation and traditional ceiling-based ventilation also obtained from numerical simulation. The conditions are described in Table. 3.2. In case #2, the air exhaust opening is ceiling-mounted return, and the vertical airflow direction was opposite to the gravity direction. Therefore, it was observed in Fig. 3.10. and Fig. 3.11. that at 600 s, the remaining acetone was "sinking" beside the walls and accumulated in corner regions. The dense gaseous gravity effect near the contamination source is also applicable in the breathing zone.

These two scenarios demonstrated that the air exhaust has a significant impact on the dispersion of dense gaseous pollution under the daily low-speed ventilation scheme. The source of dense gaseous pollution close to the exhaust location is easier to be eliminated; on the other hand, the source of dense gaseous pollution far from the exhaust has a low diffusion rate, is simple to accumulate in certain regions.

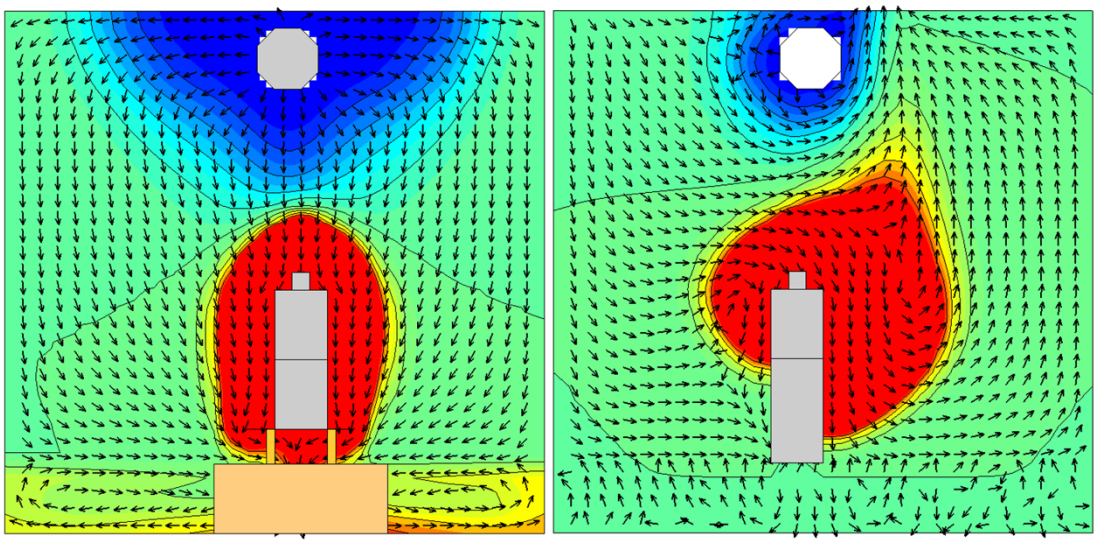
Table 3.2

The configuration of in simulations

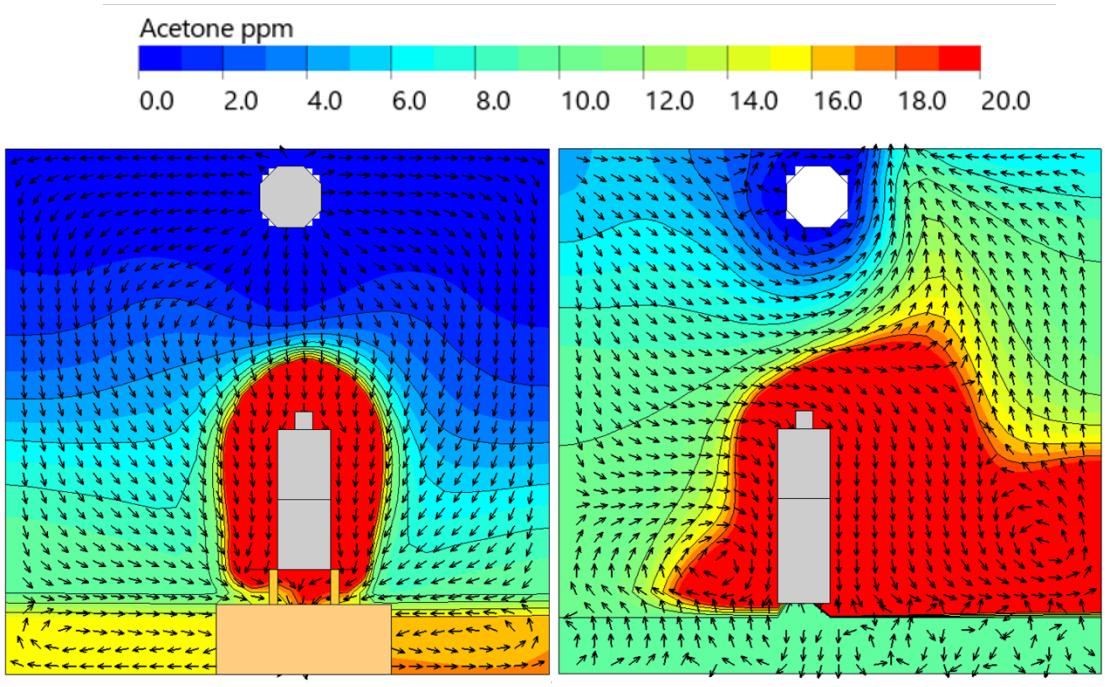
Case No.	CMH	Exhaust location	Releasing duration	Acetone background concentration
1	600	center	3 min	10 ppm
2	600	ceiling	3 min	10 ppm



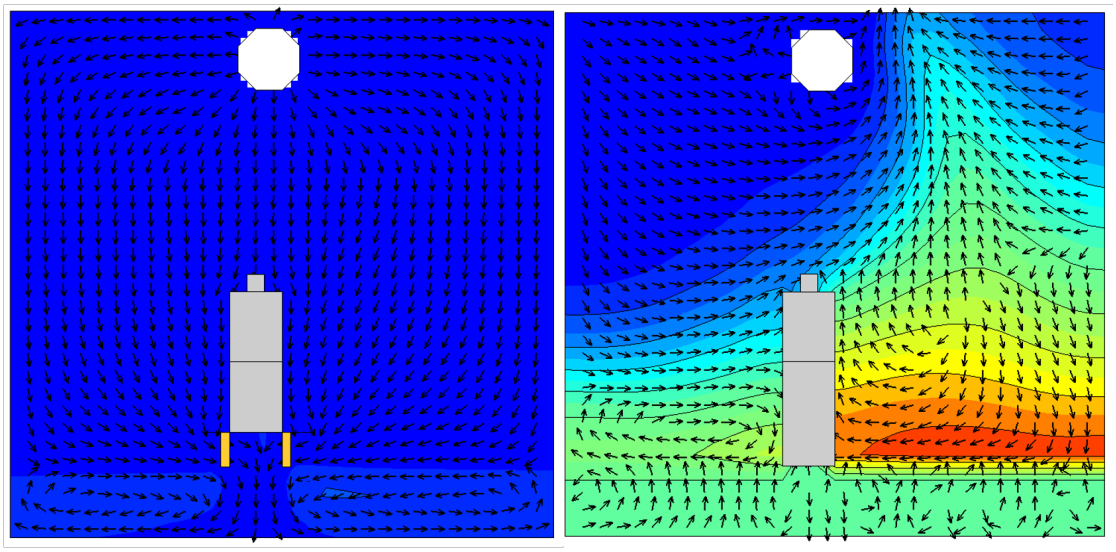
1 s (left: center; right: ceiling)



60 s (left: center; right: ceiling)

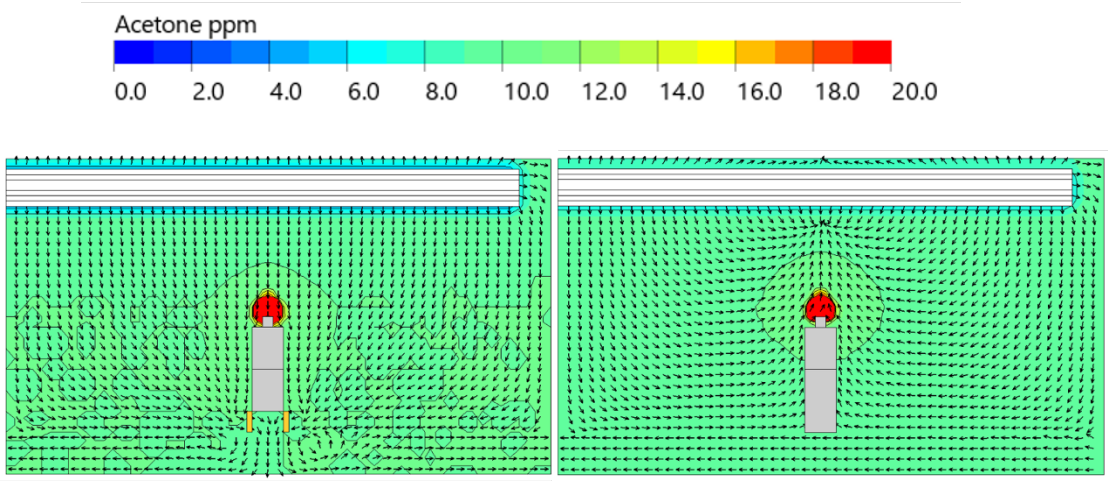


200 s (left: center; right: ceiling)



600 s (left: center; right: ceiling)

Fig. 3.10. Cloud map of acetone diffusion process (x = 2.46 m)



1 s (left: center; right: ceiling)

60 s (left: center; right: ceiling)

200 s (left: center; right: ceiling)

600 s (left: center; right: ceiling)

Fig. 3.11. Cloud map of acetone diffusion process (y = 1.426 m)

3.4 PIV Results under Different Exhaust Locations

The visualization result of PIV verified CFD simulation. In the case#1, where the exhaust location was positioned beneath the obstacle, the vectors inside the flow field flow directly to the return. In the case#2, where the exhaust location was located behind the right side of the obstacle, and the flow field was skewed to the right in order for air to reach the exhaust. The downflow ventilation in low velocity scheme can bring about local airflow pattern with downward vectors towards the exhaust.

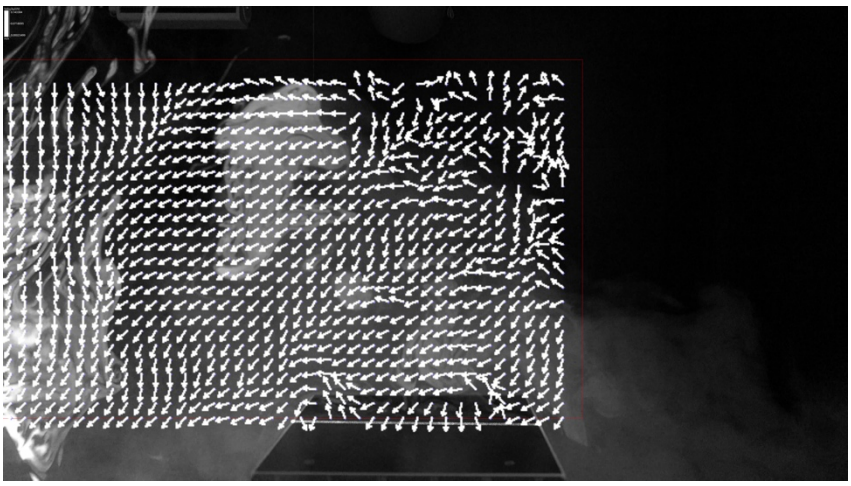


Fig. 3.11. PIV result of the airflow field with exhaust location in the center (ventilation rate: 2200 CMH)

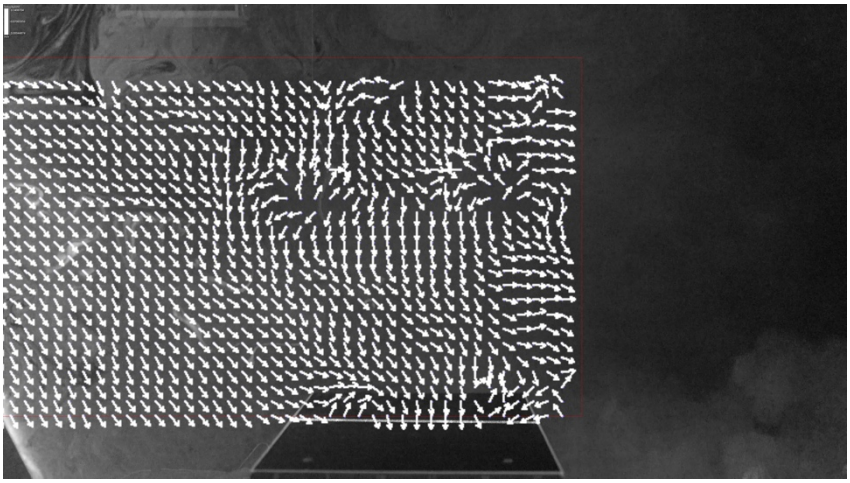


Fig. 3.12. PIV result of the airflow field with exhaust location in the corner (ventilation rate: 2200 CMH)

Chapter 4 Conclusions

This research focused on a downflow ventilation scheme using acetone as the targeted chemical under different ventilation rate and exhaust locations. It is found that

- For the dense gaseous pollution in low-velocity airflow field, the downflow ventilation is applicable for efficiently removing the dense gaseous contaminants in comparing to the traditional ceiling-mounted returns.
- For the breathing zone, increasing the ventilation rate will not necessarily bring about obvious ventilation effects. Also, the exhaust location on the floor will not have much effect on the contaminant concentration within the breathing zone.
- For the areas in the vicinity to the contamination source, the local airflow pattern plays a more important role. And general indoor ventilation system does not provide spontaneous protection from exposure to the hazardous chemicals. Ventilation requirements should combine with appropriate work practices to achieve acceptable concentrations of air contaminants.

Even though this is a case study in a simplified indoor set-up, results implied that downflow ventilation could be served as a potential candidate for efficient removal of dense gaseous contaminants. The local concentration distribution of acetone in the experimental study also presented practical implications for researchers dealing with emission sources, including limited protective level of general ventilation systems, the continuous chemical residues on the bench-top, and the safe distance to the emission sources.

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References

[1] D. Y. C. Leung, “Outdoor-indoor air pollution in urban environment: challenges and opportunity,” *Frontiers in Environmental Science*, vol. 2, 2015, Accessed: Jan. 06, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fenvs.2014.00069

[2] V. V. Tran, D. Park, and Y.-C. Lee, “Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 8, Art. no. 8, Jan. 2020, doi: 10.3390/ijerph17082927.

[3] H. Wu, Y. Mu, and J. Wang, “Effects of Different Air distributions on the Thermal Environment in the Office,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 555, no. 1, p. 012085, Aug. 2020, doi: 10.1088/1755-1315/555/1/012085.

[4] A. Essa, T. Yamanaka, T. Kobayashi, and N. Choi, “Effect of source location on contaminant dispersion pattern and occupants inhaled air quality in lecture room under displacement ventilation,” *JAPAN ARCHITECTURAL REVIEW*, vol. 6, no. 1, p. e12313, 2023, doi: 10.1002/2475-8876.12313.

[5] C. Wang, J. Liu, J. Li, Y. Guo, and N. Jiang, “Turbulence characterization of instantaneous airflow in an aisle of an aircraft cabin mockup,” *Building and Environment*, vol. 116, pp. 207–217, May 2017, doi: 10.1016/j.buildenv.2017.02.015.

[6] S. Sadrizadeh, S. Holmberg, and A. Tammelin, “A numerical investigation of vertical and horizontal laminar airflow ventilation in an operating room,” *Building and Environment*, vol. 82, pp. 517–525, Dec. 2014, doi: 10.1016/j.buildenv.2014.09.013.

[7] W. Liu, D. Liu, and N. Gao, “CFD study on gaseous pollutant transmission characteristics under different ventilation strategies in a typical chemical laboratory,” *Building and Environment*, vol. 126, pp. 238–251, Dec. 2017, doi: 10.1016/j.buildenv.2017.09.033.

[8] C. A. Mboreha, C. S. Abdallah, and G. Kumar, “RISK AND PREVENTING OF COVID-19 IN A COMMERCIAL AIRCRAFT CABIN: AN OVERVIEW,” *IJEAST*, vol. 5, no. 3, pp. 661–670, Jul. 2020, doi: 10.33564/IJEAST.2020.v05i03.115.

[9] A. Wang, Y. Zhang, Y. Sun, and X. Wang, “Experimental study of ventilation effectiveness and air velocity distribution in an aircraft cabin mockup,” *Building and Environment*, vol. 43, no. 3, pp. 337–343, Mar. 2008, doi: 10.1016/j.buildenv.2006.02.024.

[10] X. Cao *et al.*, “The on-board carbon dioxide concentrations and ventilation performance in passenger cabins of US domestic flights,” *Indoor and Built*

Environment, vol. 28, no. 6, pp. 761–771, Jul. 2019, doi: 10.1177/1420326X18793997.
[11] F. Sanchez, A. M. Huzaifa, and S. Liscouët-Hanke, "Ventilation considerations for an enhanced thermal risk prediction in aircraft conceptual design," *Aerospace Science and Technology*, vol. 108, p. 106401, Jan. 2021, doi: 10.1016/j.ast.2020.106401.
[12] A. Jangir, Md. A. N. Siddiquee, S. Mankotia, V. Tiwari, G. Vyas, and R. Choudhary, "A comparative study of ventilation system used for the bacteria prevention in operation room in healthcare units," *Materials Today: Proceedings*, vol. 50, pp. 2355–2360, 2022, doi: 10.1016/j.matpr.2021.10.237.
[13] S. Sadrizadeh *et al.*, "A systematic review of operating room ventilation," *Journal of Building Engineering*, vol. 40, p. 102693, Aug. 2021, doi: 10.1016/j.jobe.2021.102693.
[14] P. Bischoff, N. Z. Kubilay, B. Allegranzi, M. Egger, and P. Gastmeier, "Effect of laminar airflow ventilation on surgical site infections: a systematic review and meta-analysis," *The Lancet Infectious Diseases*, vol. 17, no. 5, pp. 553–561, May 2017, doi: 10.1016/S1473-3099(17)30059-2.
[15] S. Gilani, H. Montazeri, and B. Blocken, "CFD simulation of stratified indoor environment in displacement ventilation: Validation and sensitivity analysis," *Building and Environment*, vol. 95, pp. 299–313, Jan. 2016, doi: 10.1016/j.buildenv.2015.09.010.
[16] F. Davardoost and D. Kahforoushan, "Health risk assessment of VOC emissions in laboratory rooms via a modeling approach," *Environ Sci Pollut Res*, vol. 25, no. 18, pp. 17890–17900, Jun. 2018, doi: 10.1007/s11356-018-1982-6.
[17] S. Sharifi, S. Behzadi, S. Laurent, M. L. Forrest, P. Stroeve, and M. Mahmoudi, "Toxicity of nanomaterials," *Chemical Society Reviews*, vol. 41, no. 6, pp. 2323–2343, 2012, doi: 10.1039/C1CS15188F.
[18] G. C. Bell, "Optimizing laboratory ventilation rates: Process and strategies," *J. Chem. Health Saf.*, vol. 16, no. 5, pp. 14–19, Sep. 2009, doi: 10.1016/j.jchas.2009.03.013.
[19] "Classification of Laboratory Ventilation Design Levels | ASHRAE Store." https://www.techstreet.com/ashrae/standards/classification-of-laboratory-ventilation-design-levels?gateway_code=ashrae&product_id=2011313 (accessed Jan. 23, 2023).
[20] Y. Huang *et al.*, "Removal of Indoor Volatile Organic Compounds via Photocatalytic Oxidation: A Short Review and Prospect," *Molecules*, vol. 21, no. 1, Art. no. 1, Jan. 2016, doi: 10.3390/molecules21010056.

[21] “1910.1450 - Occupational exposure to hazardous chemicals in laboratories. | Occupational Safety and Health Administration.” https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1450 (accessed Jan. 23, 2023).
[22] “Globally Harmonized System of Classification and Labelling of Chemicals (GHS Rev. 9, 2021) | UNECE.” https://unece.org/transport/standards/transport/dangerous-goods/ghs-rev9-2021 (accessed Jan. 09, 2023).
[23] *ANSI/AIHA Z9.5-2012 laboratory ventilation*. Falls Church, VA: American Industrial Hygiene Association, 2012.
[24] “NFPA 45: Standard on Fire Protection for Laboratories Using Chemicals.” https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=45 (accessed Jan. 23, 2023).
[25] “NIOSH List of Antineoplastic and Other Hazardous Drugs in Healthcare Settings, 2016”.
[26] E. Sweet and R. Stuart, “Identifying general laboratory ventilation requirements using a control banding strategy,” *J. Chem. Health Saf.*, vol. 21, no. 1, pp. 9–14, Jan. 2014, doi: 10.1016/j.jchas.2013.10.001.
[27] J. F. McCarthy, M. A. Fragala, and B. J. Baker, “Analyzing the Risk: Balancing Safety and Efficiency in Laboratory Ventilation,” *ACS Chem. Health Saf.*, vol. 29, no. 5, pp. 434–440, Sep. 2022, doi: 10.1021/acs.chas.1c00095.
[28] S. H. Sagheby, “Density Effects of Gaseous Contaminants in Low Velocity Indoor Environments,” Eng.D. doi: 10.14279/depositonce-5025.
[29] Y. Cheng and Z. Lin, “Experimental study of airflow characteristics of stratum ventilation in a multi-occupant room with comparison to mixing ventilation and displacement ventilation,” *Indoor Air*, vol. 25, no. 6, pp. 662–671, 2015, doi: 10.1111/ina.12188.
[30] X. Tang, P. K. Misztal, W. W. Nazaroff, and A. H. Goldstein, “Volatile Organic Compound Emissions from Humans Indoors,” *Environ. Sci. Technol.*, vol. 50, no. 23, pp. 12686–12694, Dec. 2016, doi: 10.1021/acs.est.6b04415.
[31] Q. Zhang, X. Zhang, W. Ye, L. Liu, and P. V. Nielsen, “Experimental study of dense gas contaminant transport characteristics in a large space chamber,” *Building and Environment*, vol. 138, pp. 98–105, Jun. 2018, doi: 10.1016/j.buildenv.2018.04.020.
[32] X. Cao, J. Liu, N. Jiang, and Q. Chen, “Particle image velocimetry measurement of indoor airflow field: A review of the technologies and applications,” *Energy and Buildings*, vol. 69, pp. 367–380, Feb. 2014, doi: 10.1016/j.enbuild.2013.11.012.