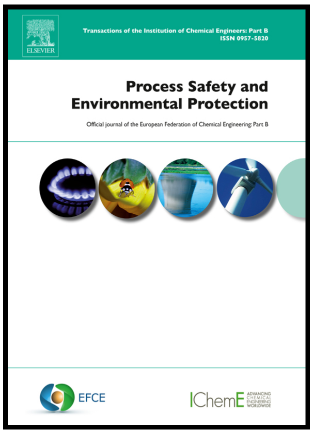

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Field investigation of Pollutant characteristics and targeted ventilation control strategies in high-ceiling aircraft spraying workshop

Lei Zhao[1], Junjie Liu[1], Yihui Yin[1], Jingjing Pei[1,*], Wu Xiao[2], Haiqiao Zhang[3], Shen Wei[4]

[1] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[2] China aviation planning and design institute (Group) co., LTD., 12 Dewai street, Xicheng District, Beijing, China
[3] China Aviation International Construction and Investment co., LTD., 12 Dewai street, Xicheng District, Beijing, China
[4] The Bartlett School of Sustainable Construction, University College London (UCL), 1-19 Torrington Place, London, WC1E 7HB, United Kingdom

[*]*Corresponding email:* jpei@tju.edu.cn

Abstract

To achieve efficient ventilation and purification in the high-ceiling painting workshop is faced with the contradiction between effect and energy consumption. Understanding the characteristics of gaseous pollutants is of paramount importance for ventilation and purification system design. The composition and concentration of volatile organic compounds (VOCs) emitted from aircraft painting workshop were sampled by Tenax-TA tubes and analyzed with gas chromatography-mass spectrometry (GC-MS). Approximately 50 types of VOCs (detection rate > 50%) were detected in the aircraft spraying workshop, with percentages of 36.3% for esters, 31.9% for aldehyde ketones, 28.5% for biphenylenes, 1.9% for alcohols and 1.4% for alkanes. The TVOC concentrations in the workshop were 48.6 mg/m^3 and 132.4 mg/m^3, during the varnish painting and the finish painting processes, respectively, and these are several times higher than those observed in other industries (automobile painting and wooden furniture painting). The field test data of spraying workshops from 197 spraying factories in five industry sectors were collected from field measurement and existing literature. Some VOCs components are the general pollutants in the painting workshops, such as Acetic acid, butyl ester, Toluene, and 2-Butanone. A novel ventilation model using multiple target purification units is proposed to eliminate the pollutants in an aircraft spraying workshop. Compared with the original trench exhaust system, the air volume of the proposed targeted ventilation system is reduced by 75%, and the energy consumption is reduced by 45,000 kW·h per aircraft.

Keywords: Aircraft spraying workshop, VOCs, Targeted ventilation, Field test, Pollution control

1. Introduction

The aviation industry has developed rapidly in recent decades, with the number of carried passengers grown by an average of 4.9% per year since 1970, and in 2006, more than two billion people traveled by flight (Boeing, 2019; Airbus, 2019; SIKA Institute, 2008). As the fleet of commercial aircraft grows, there is a foreseeable increase in maintaining aircraft in the future. Boeing has forecasted that the number of world fleet of new commercial airplanes will double by 2032, with over 35,000 new airplanes (worth about $4.8 trillion) to be built (Patrick Waurzyniak, 2016). One important phase in aircraft maintenance is the removal and repainting of finish systems to check the substrate integrity of airplanes, protecting them from corrosion to increase their lifetime (Koleske, 2012). To do both varnish and finish, an Airbus-320 flight will consume 484 kg paint per spraying work, equating to the amount required by approximately 194 automobile cars (Papasavva et al., 2002). Although an increasing number of mechanical devices have been deployed instead of human painters in most industries, some work cannot be painted automatically, especially in aircraft paintings, where the entire process is still completely in manual (Then, 1989; Morelli et al., 2018). Workers in aircraft workshops often use compressed air paint spray guns, which produce droplets that are propelled toward the surface of the aircraft by the force of compressed air. Although many droplets on the surface will form up the paint coating, the surface adhesion rate of paint is only about 40%-60%, and some droplets will be carried by the airflow around the surface and become airborne, giving paint mist pollution (Carlton and Flynn, 1997; Heitbrink and Verb, 1996). This pollution will cause a high risk on painters' health (Bari et al., 2018; Chen et al., 2019; Singh et al., 2016; Landrigan et al., 2018; Jaars et al., 2018; Singleton et al., 2016, Parveen et al., 2021) and environment (Lu et al., 2021; Emenike et al., 2020, Zhou, et al., 2020).

Controlling paint mist pollution effectively and making exhaust gas meet local environmental limits have captured great concern for paint spraying factories (Stock et al., 2018). Generally, proper ventilation (Cao et al., 2020) and pollution source control (Arsenyeva et al., 2021) are two main strategies in paint spraying factories. However, ventilation and purification systems often result in high economical consequence (J. Bennett, 2016) and energy consumption (Lin et al., 2011; Xia et al., 2011). Considering plant characteristics and technological process, proper ventilation within varied system forms has been studied. Mixing ventilation and displacement ventilation are commonly-used ventilation modes in industrial buildings, but they cannot ensure good performance efficiency in aircraft spraying workshops having high ceiling (Salmanzadeh et al., 2012; Lee & Awbi, 2004). The form of an upside-supply and floor-exhaust system has been utilized in commercial aircraft painting workshops (Guan et al., 2021; Li et al., 2013), but the performance is not satisfying due to the high ceiling in painting workshops. For pollution source control, local exhaust ventilation, such as air curtain exhaust hood (Lv et al., 2021), push-pull exhaust hood (Wang et al., 2019) and annular exhaust hood (Chen et al., 2018), have been adopted. However, as the pollution source would move with painters during the aircraft painting process, so fixed exhaust hood is not appropriate and often hampers the operation. Therefore, there is still a demand of developing an appropriate ventilation and purification method for high-ceiling painting workshops.

To control pollutants in painting workshops, understanding the characteristics of gaseous pollutants is the key, which is significant for the design and evaluation of ventilation and purification systems. Generally, the types and release characteristics of VOCs are used for purification system design and health assessment (Zhang et al., 2020; Shen et al., 2018; Jiang et al., 2013; Tong et al., 2019; Lerner et al., 2012; Wang et al., 2017). The pollution characteristics had been studied in various painting scenes, such as ship painting (Malherbe and Mandin, 2007; Celebi and Vardar, 2008), architectural painting (Gao et al., 2021), furniture painting (Qi et al., 2019), and printmaking painting (Can et al., 2015), etc. It used for health-risk assessment, atmospheric pollution assessment and ventilation control.

Due to the distinctiveness and limitations of aviation industry, studies on the emission characteristics of VOCs from aircraft painting workshops are not sufficient. Gharib et al. (Gharib et al., 2021) assessed occupational safety and health of workers in an aircraft maintenance facility and suggested that improvements in safety training, noise and heat stress management. Noweir and Zytoon (Noweir and Zytoon, 2013) evaluated the effect of excessive noise on aircraft maintenance workers’ hearing loss. Most studies of aircraft painting workshops focus on workers' hearing, ignoring the impact of pollutants on workers' health. In commercial aircraft painting workshops, increasing the air volume of ventilation systems is a common strategy to control pollution, which however is not economical and efficient (He et al., 2021; Lin et al., 2009). Therefore, field-testing in aircraft spraying workshops is necessary to collect data for a better understanding on the pollutant release characteristics.

In this study, field data were collected from 197 spraying workshops (Table S1) in five industry sectors (wooden furniture painting, rubber footwear industries, automobile painting, print painting and aircraft painting), with emission characteristics of pollutants in the aircraft painting process measured for setting boundary conditions required in building performance simulation. Based on the simulation result, a novel ventilation model using multiple target purification units has been proposed to eliminate the pollutants in aircraft spraying workshops. It is hoping that the result from this study can contribute accurate field data for VOCs pollutants evaluation and ventilation design in high-ceiling workshops.

2. Methodology

2.1 Experimental design

The hangar selected in this study is used for maintaining and spraying aircraft, with a total amount of paint usage of approximately 484 kg for each aircraft, with VOCs accounting for half of the weight. This is risky to operators' health and is also a source of pollution outdoors. To explore the concentration of pollutants in the aircraft spraying process, a thorough investigation of the production technology in this kind of workshops has been carried out in this study. The production processes and pollution discharge nodes have been detailed in the flowchart shown in Figure 1. The procedures associated with pollutant emissions are spraying varnish, spraying finish, marking coat, and drying. In the spraying process, paint particles going out of the spray gun collide on the surface of the aircraft. Some of them, however, would not adhere to the surface, but diffuse into the air. In the drying process, multiple VOCs are discharged into the air with the volatilization of a large amount of organic solvents, which poses adverse effects on operators' health. Considering the degree of pollution and restriction of investigating aircraft spraying workshops, the field measurement of this study focused on the process of spraying varnish, spraying finish, and drying.

Fig. 1 Production processes and pollution discharge nodes in the hangar.

2.2 Data collection

2.2.1 Case study hangar

In this study, a real hangar near the Shanghai Pudong International Airport has been selected for paint polishing and spraying operations. The hangar (54 m in width, 53 m in length and 17 m in height) is mainly used for medium to large aircraft, as shown in Figure 2a. Its ventilation system has one air supply module (100,000 m^3/h) located within the ceiling space of the hangar (17 m, see Figure 2c) and twelve targeted ventilation units (four with 5000 m^3/h and eight with 10000 m^3/h) around the aircraft, as shown in Figure 2b. The targeted ventilation system has replaced the original trench exhaust system. The painting capacity of this hangar is ten aircraft per year.

Fig. 2a The photograph of the hangar

Fig. 2b The photograph of targeted ventilation units

Fig. 2c The photograph of air supply module in ventilation system

As shown in Figure 3, according to the original design of this hangar, its space can be divided into four regions: 1) the spraying area; 2) the polluted area (5 m from the aircraft); 3) the control area (between 5 m and 10 m) and 4) the remaining area (beyond 10 m). The spraying area is the main pollutant zone, where the painting work is generally done. In the process of spraying, five spray guns start spraying from different parts of the aircraft, lasting or approximately 2 hours. The ventilation system is specifically designed for the polluted area, supplying 100,000 m^3/h fresh air from the ceiling of the hangar, covering the entire aircraft. The supply ventilation system is used for the drying process and inhibited pollutant diffusion. Twelve target ventilation units are placed around the aircraft to capture pollutants. Inside the control area, the pollutant concentration should be controlled under the standard level (GBZ 1-2002 Hygienic standards for the Design of Industrial Enterprises). The samplings were collected to evaluate the ventilation system’s performance at the edge of the control area(10 m from the aircraft). In the remaining area further than 10 m, operators do not need to wear protective implements.

2.2.2 Field measurement

Trade secrets and security restrictions, causing collecting characteristic data of spraying paint pollutants in a hangar is difficult. The solvents commonly used in painting are toluene, xylene, isopropanol, butanone, ethyl acetate, butyl acetate, 2-pentanone, 2-heptanone, etc. These solvents have low flash points, high relative air densities, and easily volatilize and burn (Wander, 2002). Spraying the entire aircraft generally lasts for approximately 2 hours, with 3-5 spray guns working at the same time. The concentration of combustible gas increases sharply near the aircraft, with increased explosion possibility as well. To avoid electrostatic spark, power supply equipment is prohibited during the painting process, so all measurement instruments adopted in this study are battery-powered. The sampling pump ran continuously to avoid electric spark happening when starting the instrument.

The composition and concentration of individual VOC were sampled by Tenax-TA tubes and analyzed with gas chromatography-mass spectrometry (GC-MS). This method has been widely used in airborne VOC measurement following by the standards (ISO 16000-6, 2011; GB/T 18883, 2020). In this study, the VOCs were active sampled by Tenax-TA tubes (0.20 g adsorbent, 60–80 mesh, Markes, UK) after the aging treatment using QC-2 pumps, made by the Beijing Institute of Labor Protection, at a flow rate of 0.2 L/min. Considering the high VOC concentration in painting process, the sampling duration at any position was set as 5 min to ensure the stability of the results and to avoid excessive concentration of breakdown sampling tube, so the total sampled air volume of Tenax-TA tubes was 1 L. The air sampler was located 1.5 m above the ground, which is a typical breathing zone for operators. During the measurement, the ventilation system was running continuously, with cross-sectional wind speed between 0.3 m/s and 0.5 m/s. The sampling points were set at 0.5 m (4 samples), 5 m (8 samples) and 10m (8 samples) distances from the aircraft, as shown in Figure 5. The Tenax-TA tubes were sealed with aluminum foil after sampling and were immediately sent to the laboratory for further analysis. To prevent transportation pollution, three trip blanks were taken and analyzed for the test. The duplicate air samples were conducted to verify the measurements results, and the mean value has been used for deep analysis. PM 2.5 concentration was collected by DUSTTRAK 8530 (TSI, USA). The height and location of the PM 2.5 sampling was the same as the VOC sampling. The sampling duration was 5 min.

Fig. 3 Distribution of the sampling locations in the hangar

2.3 Analysis of VOCs

The Tenax-TA tubes were desorbed via an athermal desorber (TD, Markes TD-100, Ltd.) using a secondary liquid nitrogen cold trap before being analyzed with gas chromatography equipment (GC, Ltd. PERSEE M7-80EI) fitted with a mass spectrometer (MS, Inc. Agilent 7890B). The temperature increase program for the GC/MS column was as followings: initial temperature at 50° C for 2 minutes, rising by 40 °C/min to 130 °C, holding for 1 minute, and then rising to 240 °C by 10 °C/min, keeping for 10 minutes. A mass spectrometer used the total ion scan mode so that the entire mass range (≤30_m/z≤300) was scanned at a frequency of 2.5 Hz. The detection limit will be about 1 ng for each chemical compound (Signal-to-noise ratio S/N = 3/1). An external standard method was used for quality assurance/quality control for the concentration of VOCs with R^2 of calibration curves higher than 0.99. Except for benzene, toluene, acetic acid, butyl ester, ethyl benzene, p/m-xylene, styrene, o-xylene, and undecane, the quantitative analysis of other VOCs was based on the response of toluene, and qualitative analysis was conducted by using the NIST mass spectrometry database. The concentrations of total VOCs (TVOCs) were defined as the sum concentrations of VOCs that retention time between hexane and hexadecane. More detailed information about the equipment models and QA/QC are available in our previous study (Pei et al., 2020).

3. Results

3.1 Pollution status of aircraft spraying workshop

3.1.1 The TVOC concentration comparisons in various spraying industries

Figure 4 shows the workshop TVOC concentration in various spraying industries. The comparison analysis includes 9 factories' field-test data. The data of the aircraft spraying industry are collected from the field test in this research in a hangar, and others are collected from the literature. Site A is the aircraft painting industry, sites B-G are the furniture spraying industries (Zhang et al., 2020; Jiang et al., 2013; Tong et al., 2019; Zhang, 2019), and sites H-J are automobile spraying industries (Tong et al., 2019; Lerner et al., 2012; Wang et al., 2017). Spraying operations generally include varnish and finish processes, where finish processes emit more VOC pollutants than varnish processes. The workshop TVOC concentration is significantly different in various spraying industries, and in site A, the varnish painting and finish painting process concentrations are 48.6 mg/m^3 and 132.4 mg/m^3, respectively. This is several times that of workshop concentrations in other factories. The spraying method, painting characteristics, work-piece dimension, and technological process will affect the concentration of pollutants in workshops in the spraying process. On the other hand, the pollutant concentration level also depends on the ventilation system and its efficiency. In hangars, the ventilation mode of upward air supply and air exhaust in a trench is widely used in aircraft spraying. This causes numerous pollutants, especially VOCs, to diffuse into the surrounding space. In the furniture and automobile industries, the wide use of exhaust hoods makes source control more efficient.

Fig. 4 Workshop TVOC concentration comparisons in various spraying industries

3.1.2 The characteristics of VOCs emitted from aircraft spraying workshop

The VOC compounds at two different processing stages were analyzed and the top 10 species have been listed in the Table 1. The TVOC concentration of varnish spraying and finish spraying are 48.6 mg/m3 and 132.4 mg/m3. Although the TVOC concentration difference between them is nearly three times, there is little difference in their composition. As shown in Table 1, seven components were detected both in varnish spraying and finish spraying. The main emitting components in varnish spraying are Acetic acid, butyl ester, 2-Heptanone and Methyl Isobutyl Ketone. And the main emitting components in finish spraying are Acetic acid, butyl ester, 1-Methoxy-2-propyl acetate and Toluene. These total VOCs were sorted into six classes of compounds based on their functional groups, including esters, alkanes, aldehyde ketones, alcohols, biphenylenes, and others. The contributions of the six classes of VOCs in the two stages are presented in Figure 5.

Table 1: Comparison of VOCs components concentration in varnish spraying and finish spraying

As presented in Figure 5, in the VOC emissions from the varnish, esters were the most abundant class (36.3%), followed by aldehyde ketones (31.9%), biphenylenes (28.5%), alcohols (1.9%), and minor alkanes (1.4%). For the finish spraying stage, esters (54.8%) were also the most abundant components in VOC emissions, followed by aldehyde ketones (25.7%), biphenylenes (15.7%), alkanes (2.1%), and minor alcohols (0.7%). The material compositions of the two paints are similar, but the proportions of each material are different. And the VOCs components in varnish spraying and finish spraying had been analyzed.

Fig. 5 Proportions and classes of VOCs emitted from finish and varnish plants in the spraying stage

Figure 6 shows the concentration level and detected rate of components of VOCs during the varnish and finish spraying process. The detection rate of VOCs is taken as the reference value to select the target species of VOCs in the aircraft spraying process. In Figure 6, components with a detection rate of over 50% were selected, and their concentration levels were compared. The concentration of each component has a great difference, and it is generally distributed ranging from 0.01 mg/m^3 to 80.0 mg/m^3. In Figure 6, columns marked in orange indicate irritant components, and columns marked in red with dotted boxes indicate carcinogenic components. Approximately twenty components of detected VOCs and seven components of detected VOCs are irritant gases and carcinogens, which cause great potential harm to workers' health. For ventilation systems in hangars, more attention has been focused on particle control and technological process requirements. The ventilation volume needed for VOC control is higher than that needed for particle control. Large space buildings, high pollutant emission rates, and insufficient ventilation affect VOC capture and purification. Moreover, the VOC concentration level needs to be controlled to prevent the explosion of flammable gas. As limited in the standard (AQ 5215, 2013), the vapor concentration of the organic solvent should be less than 1/8 of its explosive concentration limit. As shown in Figure 6, approximately 12 species of components will become explosive when mixed with air, which is marked as a triangular icon. Some components can be used as a feature marker for explosive concentration limits in the hangar.

Fig. 6 Profile of the detection rates of detected VOCs during the spraying process

The comparison on the concentrations of irritant gases, explosive gases and carcinogenic gases with other painting workshops (footwear painting, print painting, automobile painting and wooden furniture painting) has been shown in Table 2. Evaluating from the concentration and risk of health and control, some VOCs components are the general pollutants in the painting workshops, such as Acetic acid, butyl ester, Toluene, and 2-Butanone. The characteristics of gaseous pollutants is of significant difference on the components (Table S1, Table S2) and categories (Figure S1) among the various painting workshops.

Table 2: Comparison of VOCs components concentration in different painting workshops

4.2 Exposure risk analysis in workshop

We found 14 types of components in the hangar field test that are considered harmful pollutants in the standard (GBZ 2.1, 2019). In this standard, the occupational exposure limits have two definitions. One is the permissible concentration-time weighted average (OEL-TWA), which means the average allowable exposure concentration of 8 h of working time (a day) or 40 h of working time (a week) with time as the weight. The other is the permissible concentration-short term exposure limit (OEL-STEL), which means the average concentration that allows workers to be exposed for a short period (15 min). According to the actual exposure level of workers to chemically harmful pollutants, the exposure level of workers can be divided into five levels. Five classes were used to evaluate the exposure risk according to component concentration as follows: class 0 (no contact, value <1% OEL), class I (low contact, 1%< value < 10% OEL), class II (no obvious health effect, 10%< value < 50% OEL), class III (significant contact, 50%< value < OEL), and class IV (exceed limit, value > OEL).

Table 3: Concentration and risk level of each component in the aircraft painting workshop

Table 3 shows the concentration values and exposure risk classifications of each component in the Shanghai hanger field test. We found that each substance concentration in the workshop was lower than the OEL-TWA value. Ethyl acetate and toluene can be ranked in class II, while the others are ranked in class I. This implies that mono-pollutants have little exposure. Considering the chemical cumulative exposure on the human mucous and respiratory systems, equation (1) was used to assess the mixed exposure index. When this index is over 1, mixed exposure to chemical components is over the limits, and some measures need to be taken.

$$I = \frac{C_1}{PC - TWA_1} + \frac{C_2}{PC - TWA_2} + \frac{C_3}{PC - TWA_3} + \ldots\ldots \leq 1 \qquad (1)$$

In this formula, I is the mixed exposure index, the variable C is a type of component, and PC-TWA is the limit value of this component.

We calculated the mixed exposure index in the painting workshop based on the field test data, and the value was 0.39 to 2.02. Although the single substance does not exceed the prescribed limit, operator workers' exposure to mixed substances will have a great exposure risk. Considering the trend of reducing the air volume to save energy in many industrial factories, more attention and designs need to focus on VOC pollution.

4.3 Control strategy of spraying pollution in high-ceiling painting industrial plan

4.3.1 Target ventilation

Fig. 7 a) Schematic diagram of trench ventilation in painting hangar

Fig. 7 b) Schematic diagram of target ventilation in painting hangar

The spraying hangar adopts the vertical air distribution of upper air supply and lower air discharge following by the standard (GB 50671, 2011), which forms a cover on the surface of the aircraft. The air volume of the trench ventilation system is 400,000 m^3/h. Under ideal design conditions, the paint mist could be controlled and discharged to the outside by the trench ventilation system through the purification and filtration device. The exhaust outlet usually fixed under the fuselage and could not be close to the spraying point, the capture control area is limited and paint mist collected inefficiently. As shown in Figure 7 a), spraying pollutants need to flow around the outer contour of the aircraft following the flow field, which would escape a lot in the red circle area, resulting in unfavorable capture performance. To reach the factory emission standard, a large proportion of the air volume in the ventilation system is used to dilute the concentration of pollutants in the hangar, which wastes much air volume and energy.

According to the characteristics of aircraft spraying operation, we put forward the ventilation concept of targeted ventilation. As shown in Figure 7 b), the ventilation system still adopts the form of upward air supply to provide a proper airflow environment for spraying, and the mobile targeted ventilation unit is used to replace the original trench ventilation. The design basis of this targeted ventilation system is particle and gaseous pollutant control. For the painting particle control, the flow field of spray gun had been studied based the PIV technology (Wang et al., 2022). For the painting gaseous pollutants control, the dynamic emission characteristics of painting had been studied in the laboratory. The air volume of the target ventilation unit was determined by the anti escape speed (for particle) and effective air changes per hour in the control area (for gas) though theoretical calculation. And the numbers and locations of the target ventilation units were determined by the CFD simulation. The mobile target ventilation unit has four movable capture covers, which can adjust the position according to the spraying process, shorten the distance between the capture device and the source of the pollutants, and improve the efficiency of the capture. Compared with the traditional trench ventilation system, the mobile targeted ventilation system is more flexible and energy-saving. As shown in Figure 8, the targeted ventilation system consists of 12 equipment units, which are evenly distributed around the aircraft, and its relative position can be flexibly adjusted according to the spraying. The air volume of the targeted ventilation system is

100,000 m^3/h. Compared with the trench exhaust system, the energy consumption cost of fan operation is reduced by 45,000 kWh per aircraft spraying.

Fig. 8 The layout plan and photos of target ventilation units in painting hangar

To evaluate the control effect on spraying pollutants of targeted ventilation system after one-hour operation, the concentrations of particulate matter and TVOC at the edge of the control area were compared and analyzed. The samplings were collected 10 m away the aircraft shown in the Figure 5. The concentration of PM2.5 decreased by 90.74% from 4.43 mg/m^3 to 0.41 mg/m^3, and the concentration of TVOC decreased by 73.33% from 50.09 mg/m^3 to 13.36 mg/m^3. The effect of the targeted ventilation system has also been verified by the researchers of the same research group through CFD simulation. (Liu et al., 2021)

4.4 Pollution control of painting workshop

Fig. 9 Comparative analysis of various painting pollution control methods

As shown in Figure 9, the pollution control of painting workshop can be divided into three categories: Source control, Ventilation dilution and Air suction control. These control methods can be compared and analyzed from the following four aspects: 1. Difficulty of pollution control. The difficulty of pollutant control increases with the distance from pollution source. Exhaust terminals are often used in ventilation design in painting workshop. However, due to the limited control area and low concentration of pollutants, it is the most inefficient method on painting pollution control. 2. Effect of pollution control. The effect of pollutant control decreases with the distance from pollution source, which is contrary to the difficulty of pollutant control. 3. Technical difficulty. Although the effect of source control is effective, the location and intensity of pollution source of manual spraying in high ceiling painting industrial plant will be affected by the behavior of workers. There is still a long way to go to achieve source control. 4. Investment and maintenance costs. Comparing to the source control, ventilation dilution and air suction control require a large amount of air volume and energy consumption. Meanwhile, multiple painting pollution control modes are used in the painting workshop. The total control efficiency should be considered on the design of painting pollution control system as shown in Equation (2). The purification efficiency shows the capacity of a purification unit on the spaying pollution. The capture efficiency shows the performance of air distribution in the spraying workshop. And the operation efficiency shows the capability of the purification unit management.

$$\eta_T = \eta_P \bullet \eta_C \bullet \eta_O \qquad (2)$$

where η_T is the total control efficiency (%) of a ventilation system; η_P is the purification efficiency (%); η_C is the capture efficiency (%), and η_O is the operation efficiency (%).

4. **Limitations and Discussion**

Although a total of 20 samples were taken in a hangar, the number of industries may have been insufficient when evaluating the pollution level of the paint industry in terms of the paint type and process characteristics. This paper is mainly focused on providing qualitative information (based on field sampling and a GC/MS analysis) of VOC species in the aircraft hangar. In addition to this qualitative information, the concentration levels of various VOCs are also of interest. For those VOCs with lower detection rates (i.e., less than 50%), it may also be meaningful to further analyze the paint worker’s health risk and effect on discharged filters.

Considering the aircraft dimensions and spraying process characteristics, air velocity control has been widely used in aircraft spraying workshop for spraying process rather than source exhaust in other spraying industries. The Occupational Safety and Health Administration (OSHA) standard, 29 CFR 1910.94–Ventilation, requires that spray booths maintain an air velocity in a spray area cross-section of 100 FPM (0.508 m/s) (Code of Federal Regulations, 1989). However, the design concept of air velocity control aims to control particulate pollution rather than gaseous pollution. Many gaseous pollutants will be released in the process of spraying with the production of particles and spread to the surrounding environment. Ventilation and purification systems are often in a state of inefficient operation for gas pollutants. Aircraft spraying occupations in hangars lead to acute and chronic exposure to a high level of VOCs compared to other occupations (Vaajasaari et al., 2004; Ramírez et al., 2012; Zhang et al., 2020).

As shown in Figure 10, for ventilation design in the painting workshop, technological requirements, production safety, and environmental pollution are the main considerations. Workers' health and the effectiveness of purification equipment are rarely considered in ventilation system design. With the reduction in air volume to meet the energy-saving requirements, the concentration of pollutants in the workplace increases sharply. General labor protection is insufficient for workers exposed to mixed pollutants in some high pollution workshops. High-concentration pollution is also harmful to the effectiveness of purification equipment. On the other hand, in the aircraft paint industry, almost all ventilation and technological requirements are focused on paint particle pollution. In this paper, we found that paint workers dressed in normal labor protection (gas mask and protective suits) in hangars face occupational health risks when they are exposed to high concentrations of VOCs. We also found that PP filter purification efficiency will be affected by VOC pollutants (Jasper et al., 2007; Choi et al., 2015; Sachinidou et al., 2018). Therefore, the source characteristics and concentration level of gaseous pollutants in a painting workshop are vitally important for ventilation and purification design and worker protection in further research.

Fig. 10 Relationship between paint industry ventilation design and paint pollution

Industrial emissions are the largest anthropogenic source of VOCs in China (Liu et al., 2008). Painting operations, as essential procedures in many industries, generated approximately 1883 and 2235 kt of VOCs in 2005 and 2010, respectively, which accounted for 13% of anthropogenic emissions in China, and will approach 5673 kt in 2020 with an assumed absence of regulation (Wei et al., 2009; Klimont et al., 2002). Most Chinese paint factories mainly focus on particle extraction and pay less attention to VOC control. A large amount of ventilation is used to dilute the concentration of pollutants to meet environmental emission standards. Considering the energy consumption pressure on ventilation, an increasing number of scholars have proposed the circulation ventilation mode. The circulation ventilation mode can reduce the fresh air volume and improve ventilation efficiency. The purification efficiency of VOCs in the factory is low, and their characteristics and source release concentrations are not clear, which leads to the circulation ventilation mode not being widely used. Therefore, in this paper we proposed a methodological study on pollutant characteristics based on field test data. Further studies need to be performed by other scholars to provide quantitative conclusions.

5. **Conclusion**

Numerous paints are used in the spraying industry, resulting in serious pollution. To achieve efficient ventilation and purification in the workshop is faced with the contradiction between effect and energy consumption. This contradiction is particularly prominent in high-ceiling painting workshops, especially the aircraft painting workshop. It is found that the traditional ventilation system is inefficient and wastes energy. Researchers and designers lack understanding of the pollutant source characteristics in the aircraft painting workshop, and are unable to carry out the system optimization design according to the characteristic pollutants. This study aimed to understand the VOC species and their concentration levels in aircraft spraying workshops based on results from field measurements and statistical analysis. A targeted ventilation system was proposed and the effect had been verified in an aircraft painting workshop. The following conclusions may be drawn from this study:

1. The pollution caused by finish spraying is about three times that of varnish spraying. Approximately 50 species of VOCs (detection rate >50%) in the hangar were detected during the finish spraying, with percentages of 54.8% for esters, 25.7% for aldehyde ketones, 15.7% for biphenylenes, 2.1% for alkanes, and 0.7% for alcohols.

2. The TVOC concentrations in the workshop's polluted area (painters' activity area) are 48.6 mg/m3 and 132.4 mg/m3 during the varnish painting and finish painting process, which are several times higher than those in other industries. The health exposure risk of workers was evaluated based on Chinese standards.

3. Compared with the original trench exhaust system, the air volume of the proposed targeted ventilation system is reduced by 75%, and the energy consumption is reduced by 45,000 kW·h per aircraft.

Although we have proposed a targeted ventilation system and verified its effect in an aircraft painting workshop. Many quantitative parameters in this system still need lots of research work, including system air volume matching, unit number, unit location and so on. Meanwhile, some CFD simulation tools should be introduced to promote the design of ventilation system in high-ceiling painting workshops. The ventilation of industrial workshops should be on demand according to the process characteristics and pollutant characteristics in the future.

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Declaration of interest statement

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

References

Airbus, 2019. http://www.airbus.com/en/corporate/gmf/

Arsenyeva, O., Kleme, J.J., Kapustenko, P., Fedorenko, O., Kusakov, S., Kobylnik, D.. 2021. Plate heat exchanger design for the utilisation of waste heat from exhaust gases of drying process. *Energy*. 233, 121186. https://doi.org/10.1016/j.energy.2021.121186

Bari, M.A., Kindzierski. W.B.. 2018. Ambient volatile organic compounds (VOCs) in Calgary, Alberta: Sources and screening health risk assessment. *Sci. Total Environ.* 631–632, 627–640. https://doi.org/10.1016/j.scitotenv.2018.03.023

Bennett, J.S., Marlow, D.A., Nourian, F., Breay, J., Hammond, D.. 2016. Hexavalent chromium and isocyanate exposures during military aircraft painting under crossflow ventilation, *J. Occup. Environ. Hyg.* 13, 356–371. https://doi.org/10.1080/15459624.2015.1117617

Boeing, 2019. http://www.boeing.com/commercial/cmo

Carlton, G.N., Flynn, M.R.. 1997. A Model to Estimate Worker Exposure to Spray Paint Mists. *Appl. Occ. Environ. Hyg.* 12, 375–382. http://dx.doi.org/10.1080/1047322X.1997.10389521

Can, E., Üzmez, Ö. Ö., Döğeroğlu, T., Gaga, E. O.. 2015. Indoor air quality assessment in painting and printmaking department of a fine arts faculty building. *Atmos. Pollut. Res.* 6, 1035-1045. http://dx.doi.org/10.1016/j.apr.2015.05.008

Cao, Z., Zhai, C., Wang, Y., Zhao, T., Wang, H.. 2020. Flow characteristics and pollutant removal effectiveness of multi-vortex ventilation in high pollution emission industrial plant with large aspect ratio. *Sust. Cities Soc.* 54, 101990. https://doi.org/10.1016/j.scs.2019.101990

Castaño, B.P., Ramírez, V., Cancelado, J.A.. 2019. Controlling painters' exposure to volatile organic solvents in the automotive sector of southern Colombia. *Saf. Health Work.* 10, 355–361. https://doi.org/10.1016/j.shaw.2019.06.001

Celebi, U.B., Vardar, N.. 2008. Investigation of VOC emissions from indoor and outdoor painting processes in shipyards. *Atmos. Environ.* 42, 5685-5695.

https://doi.org/10.1016/j.atmosenv.2008.03.003

Chen, C., Lin, H., Lung, C., Chen, F., Wang, V., Chou, T., Lai, H.. 2019. Environmental concentration of spray paint particulate matters causes pulmonary dysfunction in human normal bronchial epithelial BEAS-2B cell. *Process Saf. Environ. Prot*. 126, 250–258. https://doi.org/10.1016/j.psep.2019.04.013

Chen, W., Liu, J., Mak, C.M., Wang, P., Zhao, L., Wong, H.M.. 2018. Near fields of annular slotted hoods measured via 2D-PIV. *Build. Environ.* 144, 1–8. https://doi.org/10.1016/j.buildenv.2018.08.004

China AQ 5215-2013. Testing method for the safety performance of spray booth. General Administration of work safety, Beijing (in Chinese).

China GB/T 18883-2020. Indoor Air Quality Standard. Administration of Quality Supervision Inspection and Quarantine, Beijing (in Chinese).

China GB 50671-2011. Codes for design of aircraft spraying hangar. Administration of Market Supervision, Beijing (in Chinese).

China GBZ 2.1-2019. Occupational exposure limits for hazardous factors in the Workplace Part 1: chemical hazardous factors. State Health Commission of the people's Republic of China, (in Chinese).

Choi, H.J., Park, E.S., Kim, J.U., Kim, S.H., Lee, M.H.. 2015. Experimental study on charge decay of electret filter due to organic solvent exposure. *Aerosol Sci. Technol*. 49, 977-983. https://doi.org/10.1080/02786826.2015.1086724

Code of Federal Regulations, Part 1910: Occupational Safety and Health Standards, Subpart G: Occupational Health and Environmental Control, Standard 1910.94: Ventilation, Section (c)(6): Velocity and airflow requirements.

Emenike, P.C., Tenebe, I.T., Neris, J.B., Omole, D.O., Afolayan, O., Okeke, C.U., Emenike, I.K.. 2020. An integrated assessment of land-use change impact, seasonal variation of pollution indices and human health risk of selected toxic elements in sediments of River Atuwara, Nigeria. *Environ. Pollut.* 265, 114795. https://doi.org/10.1016/j.envpol.2020.114795

Estevan, C., Ferri, F., Sogorb, M.A., Vilanova, E.. 2012. Characterization and evolution of exposure to volatile organic compounds in the Spanish shoemaking industry over a 5-year period. *J. Occup. Environ. Hyg*. 9, 653–662. https://doi.org/10.1080/15459624.2012.725012

Gao, M., Teng, W., Du, Z., Nie, L., An, X., Liu, W., Sun, X., Shen, Z., Shi, A.. 2021. Source profiles and emission factors of VOCs from solvent-based architectural coatings and their contributions to ozone and secondary organic aerosol formation in China. *Chemosphere*. 275, 129815. https://doi.org/10.1016/j.chemosphere.2021.129815

Gharib, S., Martin, B., Neitzel, R.L.. 2021. Pilot assessment of occupational safety and health of workers in an aircraft maintenance facility. *Saf. Sci.* 141, 105299. https://doi.org/10.1016/j.ssci.2021.105299

Gioda, A., Neto, F.R.d.A.. 2002. Exposure to high levels of volatile organic compounds and other pollutants in a printing facility in Bio de Janeiro, Brazil. *Indoor Built Environ.* 11, 302–311. https://doi.org/10.1159/000066528

Guan, B., Liu, X., Zhang. T.. 2021. Energy performance analysis on segmented liquid desiccant air-conditioning system for bus spray-paint booths. *J. Clean. Prod.* 278, 123898. https://doi.org/10.1016/j.jclepro.2020.123898

Guan, J. , Wang, C. , Gao, K. , Yang, X., Lin, C. H. , Lu, C.. 2014. Measurements of volatile organic compounds in aircraft cabins. part ii: target list, concentration levels and possible influencing factors. *Build. Environ.* 75, 170-175. http://dx.doi.org/10.1016/j.buildenv.2014.01.023

Hasani, I.W., Sharaf, N.E., El-Desouky, M.A., Shakour, A.A.A., Mohamed, M.S.. 2015. Hepatic impairment among workers of furniture manufacture occupationally exposed to solvents in Egypt. *Journal of The Arab Society for Medical Research.* 10, 82–87. https://doi.org/10.4103/1687-4293.175891

Heitbrink, W.A., Verb, R.H., Fischbach, T.J., Wallace, M.E.. 1996. A comparison of conventional and high volume-low pressure spray-painting guns. *Am. Ind. Hyg. Assoc. J.* 57, 304–310. https://doi.org/10.1080/15428119691015043

He, Y., Hii, D., Wong, N.H., Peck, T.G.. 2021. Unsteady rans simulations of laboratory ventilation with chemical spills and gas leakages - toward balanced safety and energy effectiveness. *Build. Environ.* 191, 107576.

https://doi.org/10.1016/j.buildenv.2020.107576

ISO 16000-6:2011. Indoor air — Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID.

Jaars, K., Vestenius, M., van Zyl, P.G., Beukes, J.P., Hellén, H., Vakkari, V., Venter, M., Josipovic, M., Hakola, H.. 2018. Receptor modelling and risk assessment of volatile organic compounds measured at a regional background site in South Africa. *Atmos. Environ.* 172, 133–148 https://doi.org/10.1016/j.atmosenv.2017.10.047

Jasper, W., Mohan, A., Hinestroza, J.P., Barker, R.L.. 2007. Degradation processes in corona-charged electret filter-media with exposure to ethyl benzene, *J. Eng. Fiber Fabr.* 2, 19-24. https://doi.org/10.1108/09556220710819555

Jiang, C., Li, S., Zhang, P., Wang, J.. 2013. Pollution level and seasonal variations of carbonyl compounds, aromatic hydrocarbons and TVOC in a furniture mall in Beijing, China. *Build. Environ.* 69, 227–232. https://doi.org/10.1016/j.buildenv.2013.08.013

Klimont, Z., Streets, D.G., Gupta, S., Cofala, J., Fu, L., Ichikawa, Y., 2002. Anthropogenic emissions of non-methane volatile organic compounds in China. *Atmos. Environ.* 36, 1309–1322. http://dx.doi.org/10.1016/S1352-2310(01)00529-5

Koleske, J.V.. 2012. Paint and coating testing manual: Fifteenth edition of the gardner-sward handbook. ASTM manual series. ASTM International. https://books.google.pt/books?id=5SlHpwAACAAJ

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Baldé, A.B., Bertollini, R., Bose-O’Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, A.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potocnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2018. *The Lancet Commission on pollution and health. Lancet* 391, 462－512. http://dx.doi.org/10.1016/S0140-6736(17)32345-0

Lee, H., Awbi, H.B.. 2004. Effect of internal partitioning on indoor air quality of rooms with mixing ventilation—Basic study. *Build. Environ.* 39, 127–141. https://doi.org/10.1016/j.buildenv.2003.08.007

Lerner, J.E.C., Sanchez, E.Y., Sambeth, J.E., Porta, A.A.. 2012. Characterization and health risk assessment of VOCs in occupational environments in Buenos Aires, Argentina. *Atmos. Environ.* 55, 440–447. https://doi.org/10.1016/j.atmosenv.2012.03.041

Li, G., Wei, W., Shao, X., Nie, L., Wang, H., Yan, X., Zhang, R.. 2018. A comprehensive classification method for VOC emission sources to tackle air pollution based on VOC species reactivity and emission amounts. *J. Environ. Sci.* 67, 78–88. https://doi.org/10.1016/j.jes.2017.08.003

Li, J., Uttarwar, R.G., Huang, Y.. 2013. CFD-based modeling and design for energy-efficient VOC emission reduction in surface coating systems. *Clean Technol. Environ. Policy.* 15, 1023–1032. https://doi.org/10.1007/s10098-013-0583-9

Li, Q., Su, G., Li, C., Wang, M., Tan, L., Gao, L., Wu, M., Wang, Q.. 2019. Emission profiles, ozone formation potential and health-risk assessment of volatile organic compounds in rubber footwear industries in China. *J. Hazard. Mater.* 375, 52–60. https://doi.org/10.1016/j.jhazmat.2019.04.064

Lin, B., Wu, Y., Zhang, L.. 2011. Estimates of the potential for energy conservation in the Chinese steel industry. *Energy Policy.* 39, 3680–3689. https://doi.org/10.1016/j.enpol.2011.03.077

Lin, C.C., Yu, K.P., Zhao, P., Lee, W.M.. 2009. Evaluation of impact factors on voc emissions and concentrations from wooden flooring based on chamber tests. *Build. Environ.* 44, 525-533. https://doi.org/0.1016/j.buildenv.2008.04.015

Liu, F., Zhang, T.T., Zhang, H., Huo, Q., Wang, J., Long, Z., Liu, J.. 2021. Removing painting-generated VOCs in a commercial airplane hangar with multiple portable exhaust hoods. *Build. Environ.* 196, 107797. https://doi.org/10.1016/j.buildenv.2021.107797

Liu, J.F., Zhao, J., Li, T.T.. 2008. Establishment of Chinese anthropogenic source volatile organic compounds emission inventory. *China Environ. Sci.* 28, 496–500. (in Chinese)

Liu, L., Cai, H., Chao, L.. 2012. Volatile organic compounds (VOCs) emission characteristics study of shoemaking industry. *Guangdong Chemical Industry.* 39, 288–290.

Lu, C., Wang, X., Zhang, J., Liu, Z., Liang, Y., Dong, S., Li, M., Chen, J., Chen, H., Xie, H., Xue, L., Wang, W.. 2021. Substantial emissions of nitrated aromatic compounds in the particle and gas phases in the waste gases from eight industries. *Environ. Pollut.* 283, 117132. https://doi.org/10.1016/j.envpol.2021.117132

Lv, L., Gao, J., Zeng, L., Cao, C., Zhang, J., He, L.. 2021. Performance assessment of air curtain range hood using contaminant removal efficiency: An experimental and numerical study. *Build. Environ.* 188, 107456. https://doi.org/10.1016/j.buildenv.2020.107456

Ma, Z., Liu, S., Qiu S., Wu, T.. 2016. Characteristics of volatile organic compound emission from the automobile painting industry in Shandong province. *Environmental Protection Science.* 42, 133–138. https://doi.org/10.16803/j.cnki.issn.1004-6216.2016.04.027

Malherbe, L., Mandin, C.. 2007. VOC emissions during outdoor ship painting and health-risk assessment. *ATMOS ENVIRON*. 41, 6322-6330. https://doi.org/10.1016/j.atmosenv.2007.02.018

Morelli, U., Dalla Vedova, M.D.L., Maggiore, P.. 2018. Automatic painting and paint removal system: A preliminary design for aircraft applications. *International Conference on Robotics in Alpe-Adria Danube Region*. 640–650. https://doi.org/10.1007/978-3-030-00232-9_67

Noweir, M.H., Zytoon, M.A.. 2013. Occupational exposure to noise and hearing thresholds among civilian aircraft maintenance workers. *Int. J. Ind. Ergon.* 43, 495-502. http://dx.doi.org/10.1016/j.ergon.2013.04.001

Papasavva, S., Kia, S., Claya, J., Gunther, R.. 2002. Life cycle environmental assessment of paint processes. *J. Coat. Technol.* 74, 65–76. https://doi.org/10.1007/BF02720151

Parveen, N., Siddiqui, L., Sarif, M.N., Islam, M.S., Khanam, N., Mohibul, S.. 2021. Industries in Delhi: Air pollution versus respiratory morbidities. *Process Saf. Environ. Prot*. 152, 495–512. https://doi.org/10.1016/j.psep.2021.06.027

Pei, J., Yin, Y., Liu, J., Dai, X.. 2020. An eight-city study of volatile organic compounds in Chinese residences: compounds, concentrations, and characteristics. *Sci. Total Environ*, 698, 134137.1-134137.13. https://doi.org/10.1016/j.scitotenv.2019.134137

Qi, Y., Shen, L., Zhang, J., Yao, J., Lu, Rong., Miyakoshi, T.. 2019. Species and release characteristics of VOCs in furniture coating process. *Environ. Pollut.* 245, 810–819. https://doi.org/10.1016/j.envpol.2018.11.057

Ramírez, N., Cuadras, A., Rovira, E., Borrull, F., Rosa Maria Marcé, R.M.. 2012. Chronic risk assessment of exposure to volatile organic compounds in the atmosphere near the largest Mediterranean industrial site. *Environ. Int.* 39, 200–209. https://doi.org/10.1016/j.envint.2011.11.002

Sachinidou, P., Heuschling, C., Schaniel, J., Wang, J.. 2018. Investigation of surface potential discharge mechanism and kinetics in dielectrics exposed to different organic solvents. *Polymer*. 145, 447-453. https://doi.org/10.1016/j.polymer.2018.05.023

Salmanzadeh, M., Zahedi, Gh., Ahmadi, G., Marr, D.R., Glauser, M. 2012. Computational modeling of effects of thermal plume adjacent to the body on the indoor airflow and particle transport. *J. Aerosol. Sci.* 53, 29–39. https://doi.org/10.1016/j.jaerosci.2012.05.005

Shen, L., Xiang, P., Liang, S., Chen, W., Wang, M., Lu, S., Wang, Z.. 2018. Sources profiles of volatile organic compounds (VOCs) measured in a typical industrial process in Wuhan, Central China. *Atmosphere.* 9, 297. http://dx.doi.org/10.3390/atmos9080297

SIKA Institute, 2008. http://www.sika-institute.se/Doclib/2008/Statistik

Singh, D., Kumar, A., Kumar, K., Singh, B., Mina, U., Singh, B.B., Jain, V.K.. 2016. Statistical modeling of O_3, NOx, CO, $PM_{2.5}$, VOCs and noise levels in commercial complex and associated health risk assessment in an academic institution. *Sci. Total Environ.* 572, 586–594. http://dx.doi.org/10.1016/j.scitotenv.2016.08.086

Singleton, R., Salkoski, A.J., Bulkow, L., Fish, C., Dobson, J., Albertson, L., Skarada, J., Kovesi, T., McDonald, C., Hennessy, T.W., Ritter, T.. 2016. Housing characteristics and indoor air quality in households of Alaska native children with chronic lung conditions. *Indoor Air.* 27, 478–486. http://dx.doi.org/10.1111/ina.12315

Stock, T., Obenaus, M., Kunz, S., Kohl, H.. 2018. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. *Process Saf. Environ. Prot*. 118, 254–267. https://doi.org/10.1016/j.psep.2018.06.026

Then, M.J.. 1989. The future of aircraft paint removal methods. Master’s thesis, Air Institute of Technology, Wright - Palterson Air Force Base, Ohio, September 1989.

Tong, R., Zhang, L., Yang, X., Liu, J., Zhou, P., Li, J.. 2019. Emission characteristics and probabilistic health risk of volatile organic compounds from solvents in wooden furniture manufacturing. *J. Clean Prod.* 208, 1096–1108. http://dx.doi.org/10.1016/j.jclepro.2018.10.195

Uang, S.N., Shih, T.S., Chang, C.H., Chang, S.M., Tsai, C.J., Deshpande, C.G.. 2006. Exposure assessment of organic solvents for aircraft paint stripping and spraying workers. *Sci. Total Environ.* 356, 38–44. http://dx.doi.org/10.1016/j.scitotenv.2005.02.029

Vaajasaari, K., Kulovaara, M., Joutti, A., Schultz, E., Soljamo, K.. 2004. Hazardous properties of paint residues from the furniture industry. *J. Hazard. Mater.* 106, 71–79. http://dx.doi.org/10.1016/j.jhazmat.2003.11.004

Wander, J.D.. 2002. Cost-effective ventilation for large spray-painting operations. *Metal finishing.* 100, 23–24, 26–27.

http://dx.doi.org/10.1016/S0026-0576(02)80294-X

Wang, D., Yu, H., Shao, X., Yu, H., Nie, L.. 2017. Direct and potential risk assessment of exposure to volatile organic compounds for primary receptor associated with solvent consumption. *Environ. Pollut.* 233, 501–509. http://dx.doi.org/10.1016/j.envpol.2017.10.009

Wang, D., Nie, L., Shao, X., Yu, H.. 2017. Exposure profile of volatile organic compounds receptor associated with paints consumption. *Sci. Total Environ.* 603–604, 57–65. http://dx.doi.org/10.1016/j.scitotenv.2017.05.247

Wang, H., Nie, L., Li, J., Wang, Y., Wang, G., Wang, J., Hao, Z.. 2013. Characterization and assessment of volatile organic compounds (VOCs) emissions from typical industries. *Chin. Sci. Bull.* 58, 724-730. http://dx.doi.org/10.1007/s11434-012-5345-2.

Wang, H., Qiao, Y., Chen, C., Lu, J., Dai, H., Qiao, L., Lou, S., Huang, C., Li, L., Jing, S., Wu, J.. 2014. Source profiles and chemical reactivity of volatile organic compounds from solvent use in Shanghai, China. *Aerosol Air Qual. Res.* 14, 301–310. http://dx.doi.org/10.4209/aaqr.2013.03.0064

Wang, Q., Liu, J., Liu, J., Li, J.. 2022. Experimental research on the impact of annular airflow on the spraying flow field: A source control technology of paint mist. *Build. Environ.* 207, 108444. https://doi.org/10.1016/j.buildenv.2021.108444

Wang, Y., Quan, M., Zhou, Y.. 2019. Effect of velocity non-uniformity of supply air on the mixing characteristics of push-pull ventilation systems. *Energy.* 187, 115962. http://dx.doi.org/10.1016/j.energy.2019.115962

Waurzyniak, P.. 2016. Expanding the horizons of aerospace automation. *Manuf. Eng.* 156, 59–67.

Wei, W., Wang, S., Hao, J.. 2009. Estimation and forecast of volatile organic compounds emitted from paint uses in China. *Environ. Sci*. 30, 2809–2815. https://doi.org/10.13227/j .hjkx.2009.10.001

Wu, K., Duan, M., Zhou, J., Zhou, Z., Tan, Q., Song, D., Lu, C., Deng, Y.. 2020. Sources profiles of anthropogenic volatile organic compounds from typical solvent used in Chengdu, China. *J. Environ. Eng.-ASCE*. 146, 05020006.

http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0001739

Xia, X., Huang, G., Chen, G., Zhang, B., Chen, Z., Yang, Q.. 2011. Energy security, efficiency and carbon emission of Chinese industry. *Energy Policy.* 39, 3520–3528. http://dx.doi.org/10.1016/j.enpol.2011.03.051

Xiong, J., Wang, L., Bai, Y., Zhang, Y.. 2013. Measuring the characteristic parameters of VOC emission from paints. *Build. Environ.* 66, 65–71. http://dx.doi.org/10.1016/j.buildenv.2013.04.025

Yuan, B., Shao, M., Lu, S., Wang, B.. 2010. Source profiles of volatile organic compounds associated with solvent use in Beijing, China. *Atmos. Environ.* 44, 1919–1926. http://dx.doi.org/10.1016/j.atmosenv.2010.02.014

Zhang, J.. 2019. Emission characteristics and control technology of volatile organic compounds in wood furniture manufacturing industry (Master's thesis, South China University of Technology).

Zhang, Y., Li, C., Yan, Q., Han, S., Zhao, Q., Yang, L., Liu, Y., Zhang, R.. 2020. Typical industrial sector-based volatile organic compounds source profiles and ozone formation potentials in Zhengzhou, China. *Atmos. Pollut. Res.* 11, 841–850. https://doi.org/10.1016/j.apr.2020.01.012

Zheng, J., Yu, Y., Mo, Z., Zhang, Z., Wang, X., Yin, S., Peng, K., Yang, Y., Feng, X., Cai, H. 2013. Industrial sector-based volatile organic compound (VOC) source profiles measured in manufacturing facilities in the Pearl River Delta, China. *Sci. Total Environ.* 456–457, 127–136. http://dx.doi.org/10.1016/j.scitotenv.2013.03.055

Zhong, Z., Sha, Q., Zheng, J., Yuan, Z., Gao, Z., Ou, J., Zheng, Z., Li, C., Huang, Z.. 2017. Sector-based VOCs emission factors and source profiles for the surface coating industry in the Pearl River Delta region of China. *Sci. Total Environ.* 583, 19–28. https://doi.org/10.1016/j.scitotenv.2016.12.172

Zhou., M., Jiang, W., Gao, W., Zhou, B., Liao, X.. 2020. A high spatiotemporal resolution anthropogenic VOC emission inventory for Qingdao City in 2016 and its ozone formation potential analysis. *Process Saf. Environ. Prot.* 139, 147–160. https://doi.org/10.1016/j.psep.2020.03.040

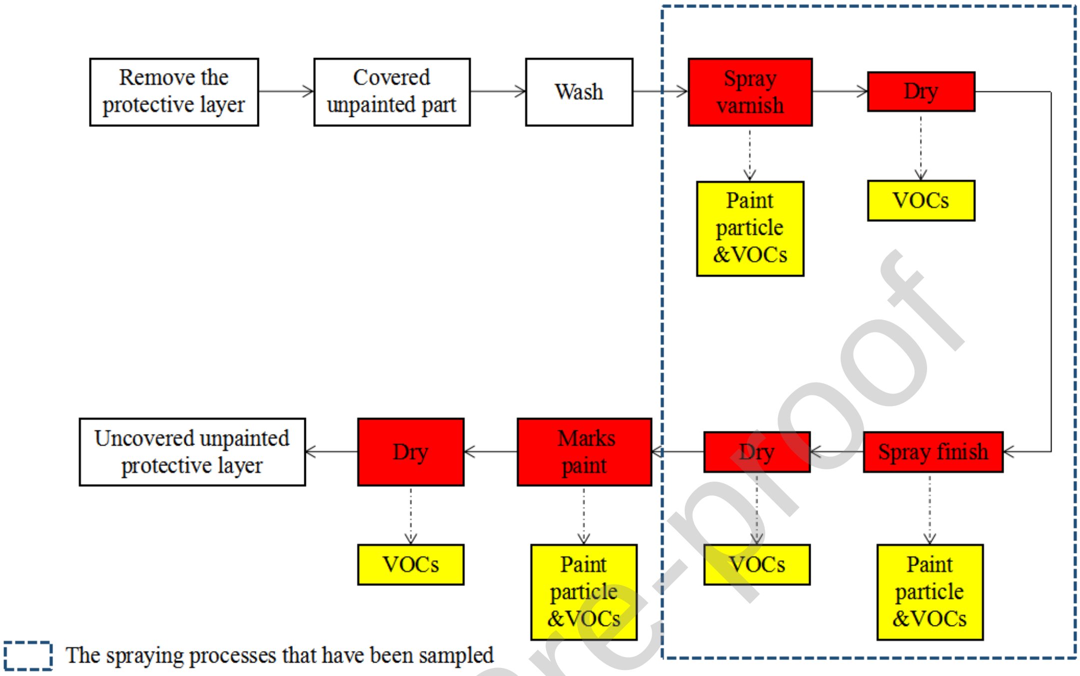

Fig. 1 Production processes and pollution discharge nodes in the hangar

Fig. 2a The photograph of the hangar

Fig. 2b The photograph of targeted ventilation units

Fig. 2c The photograph of air supply module in ventilation system

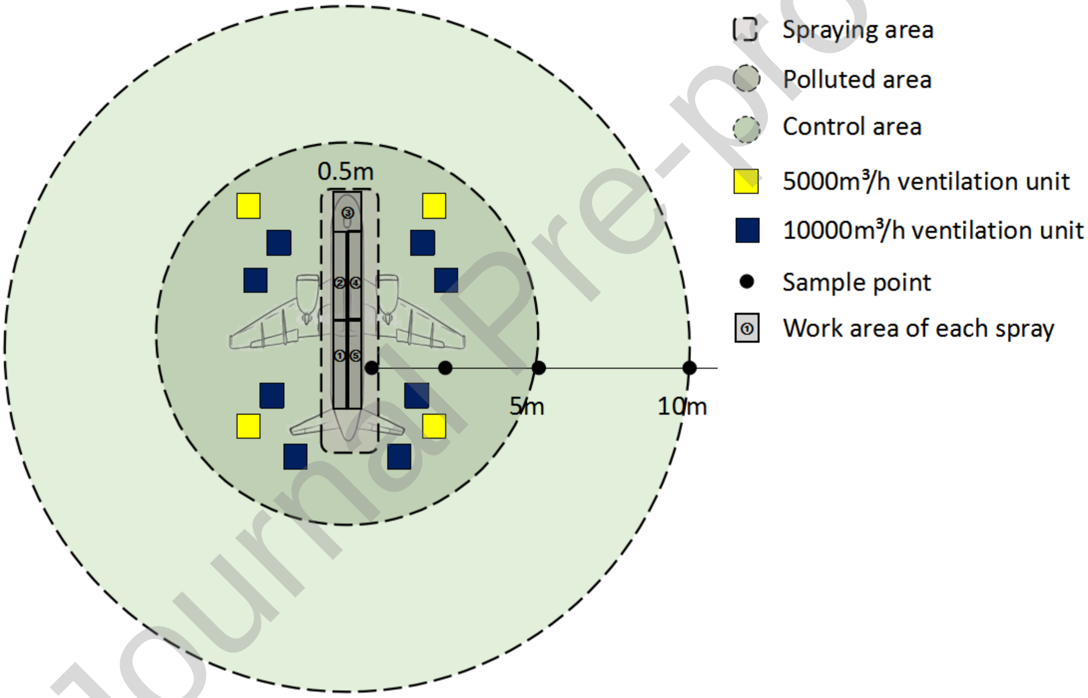

Fig. 3 Distribution of the sampling locations in the hangar

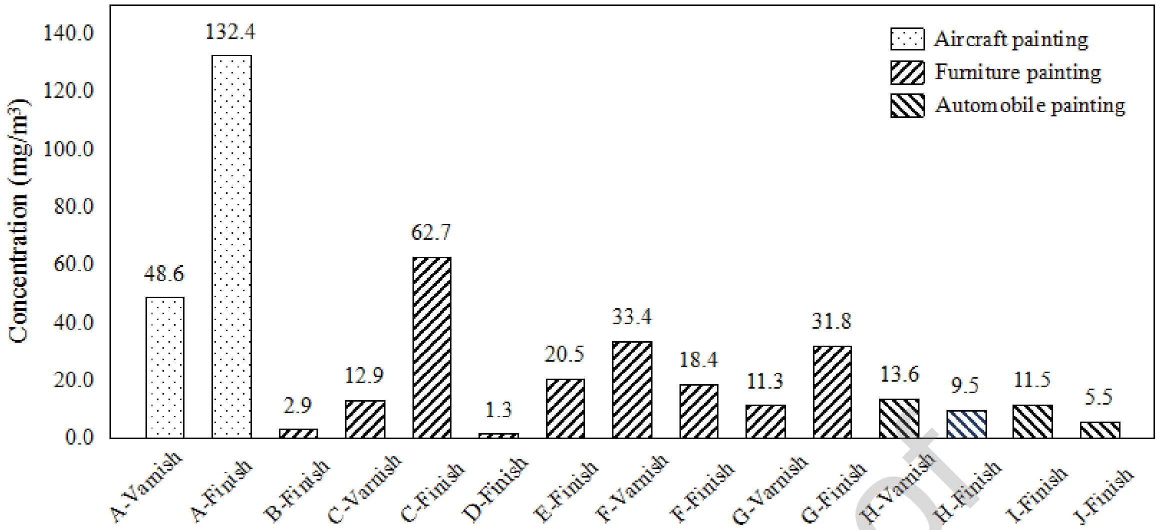

Fig. 4 Workshop TVOC concentration comparisons in various spraying industries

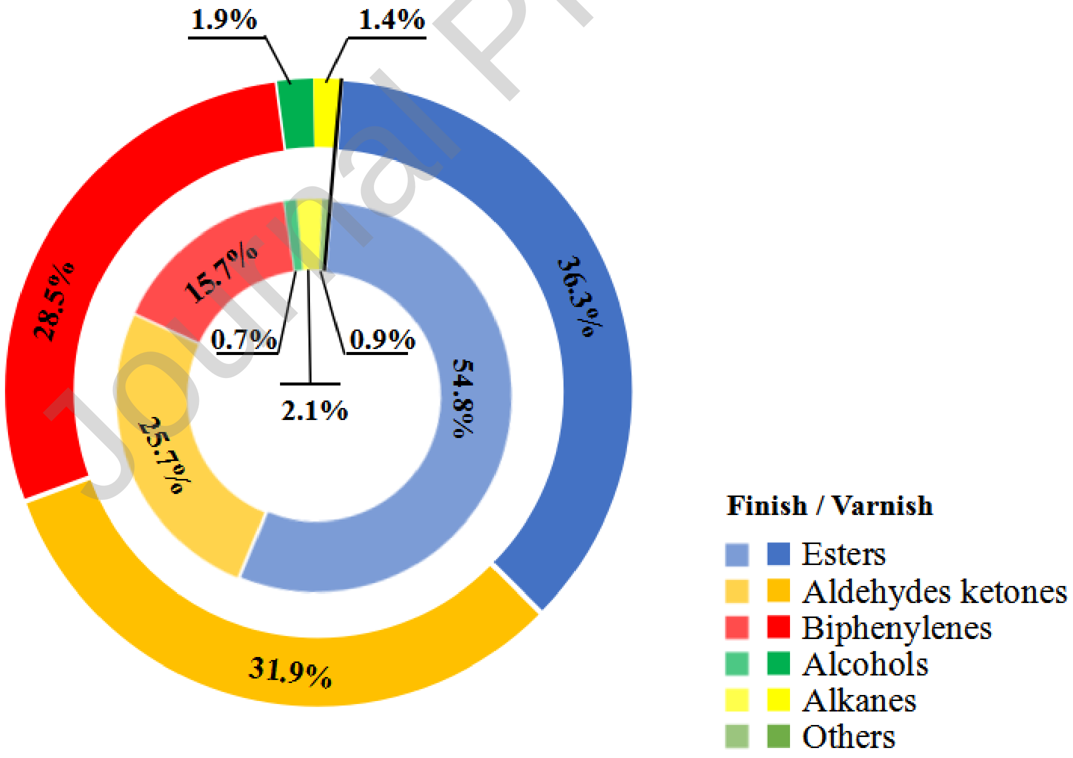

Fig. 5 Proportions and classes of VOCs emitted from finish and varnish plants in the spraying stage

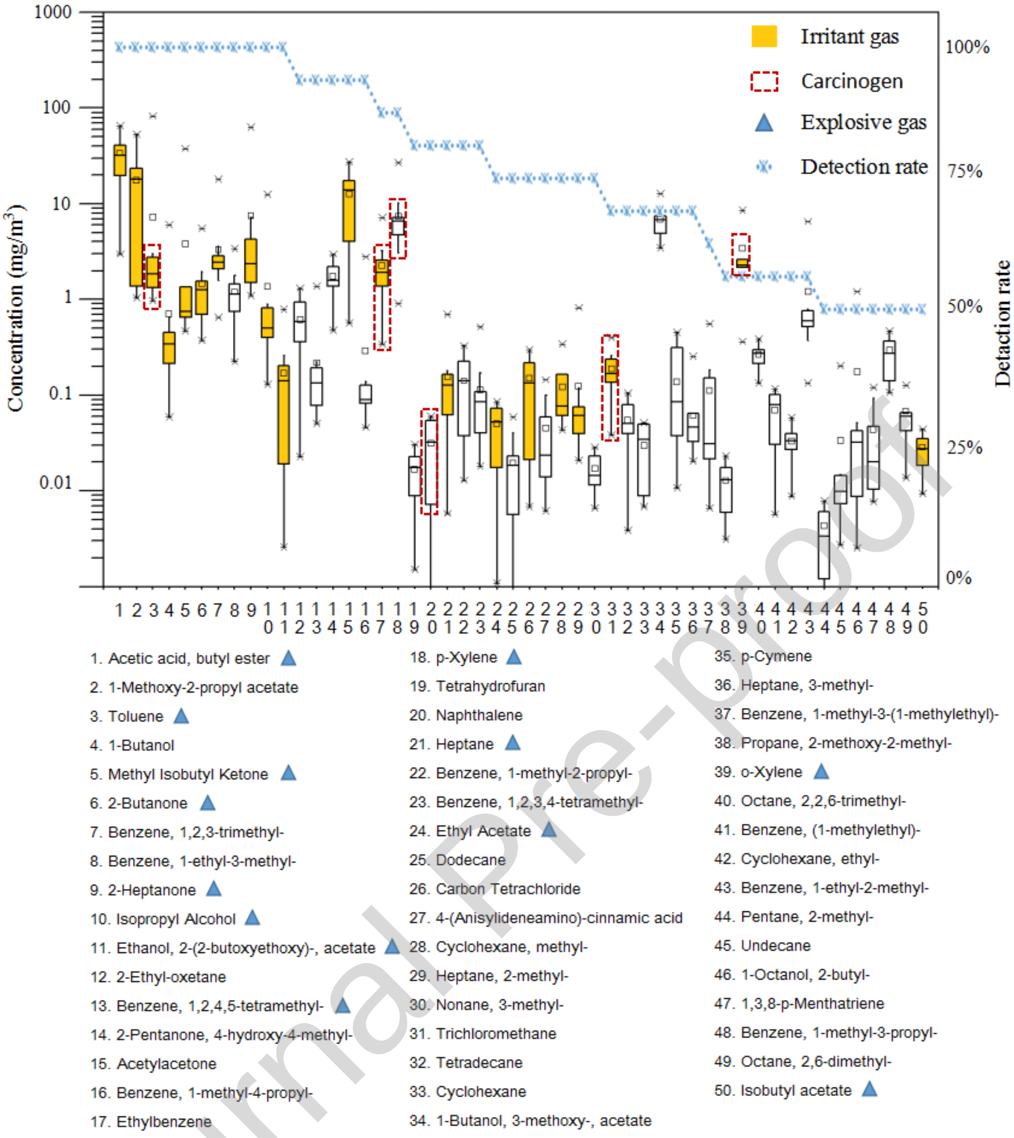

Fig. 6 Profile of the detection rates of detected VOCs during the spraying process

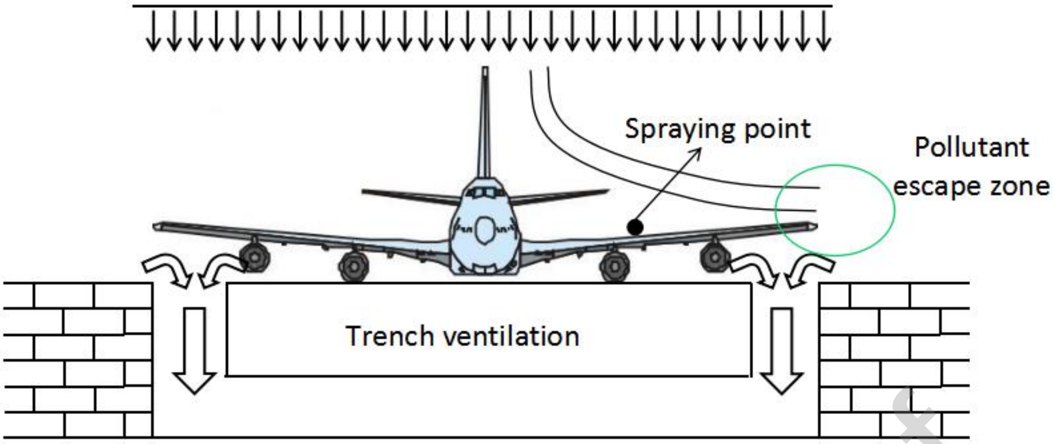

Fig. 7 a) Schematic diagram of trench ventilation in painting hangar

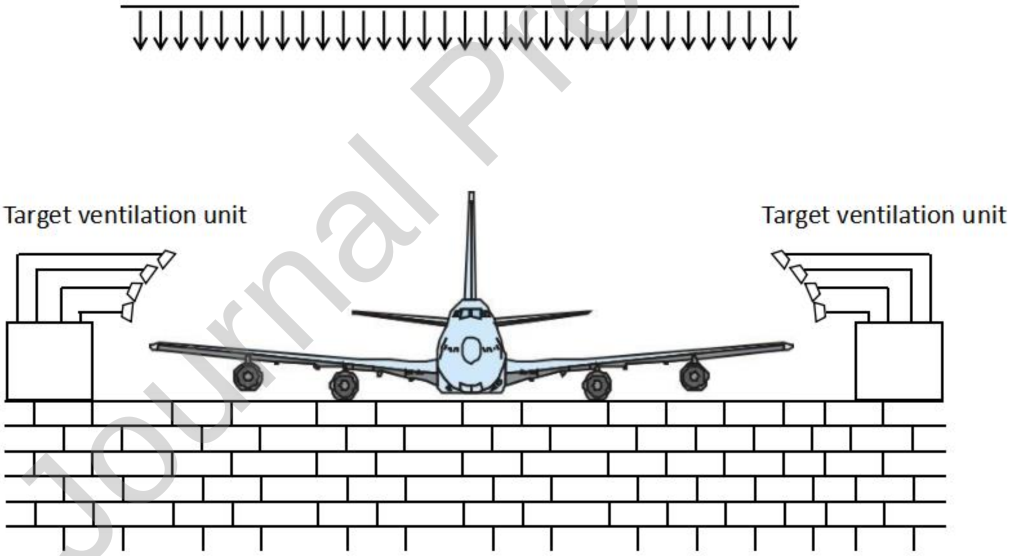

Fig. 7 b) Schematic diagram of target ventilation in painting hangar

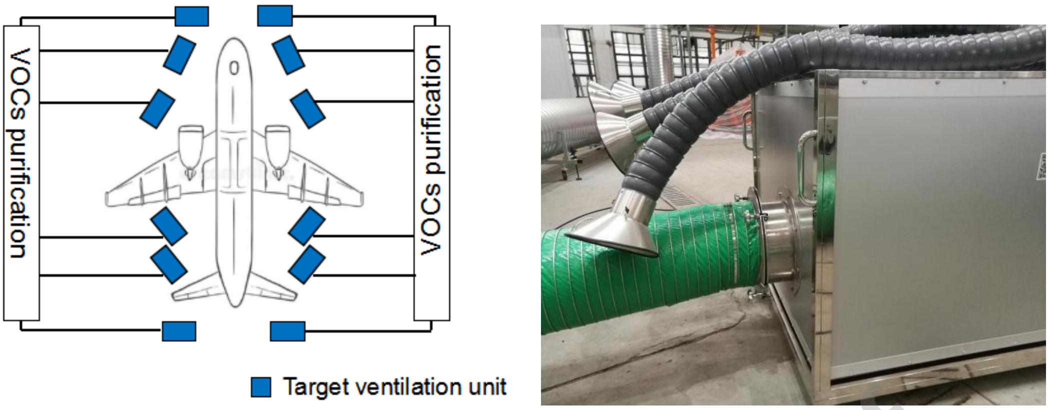

Fig. 8 The layout plan and photos of target ventilation units in painting hangar

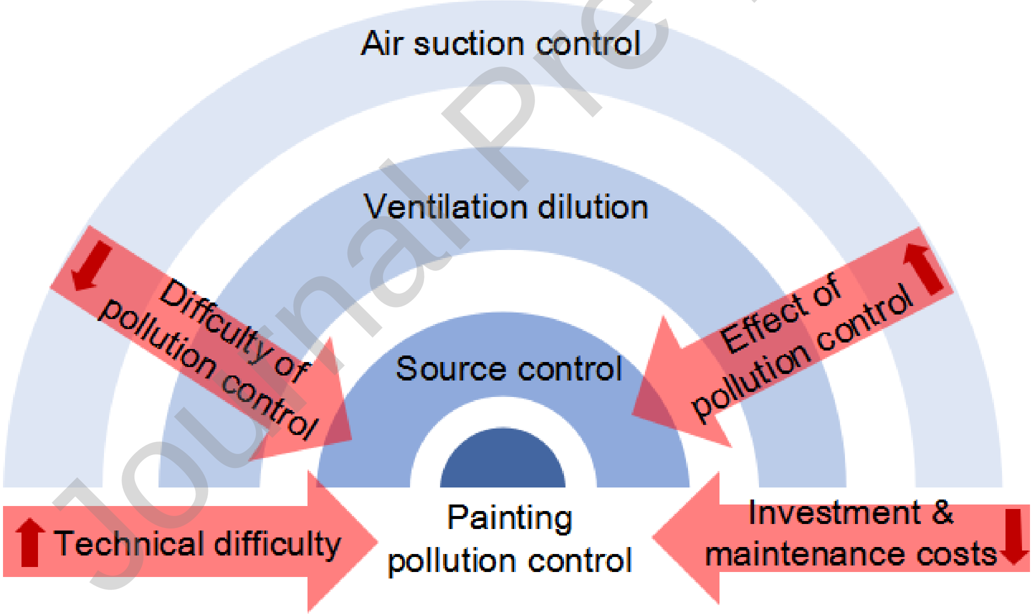

Fig. 9 Comparative analysis of various painting pollution control methods

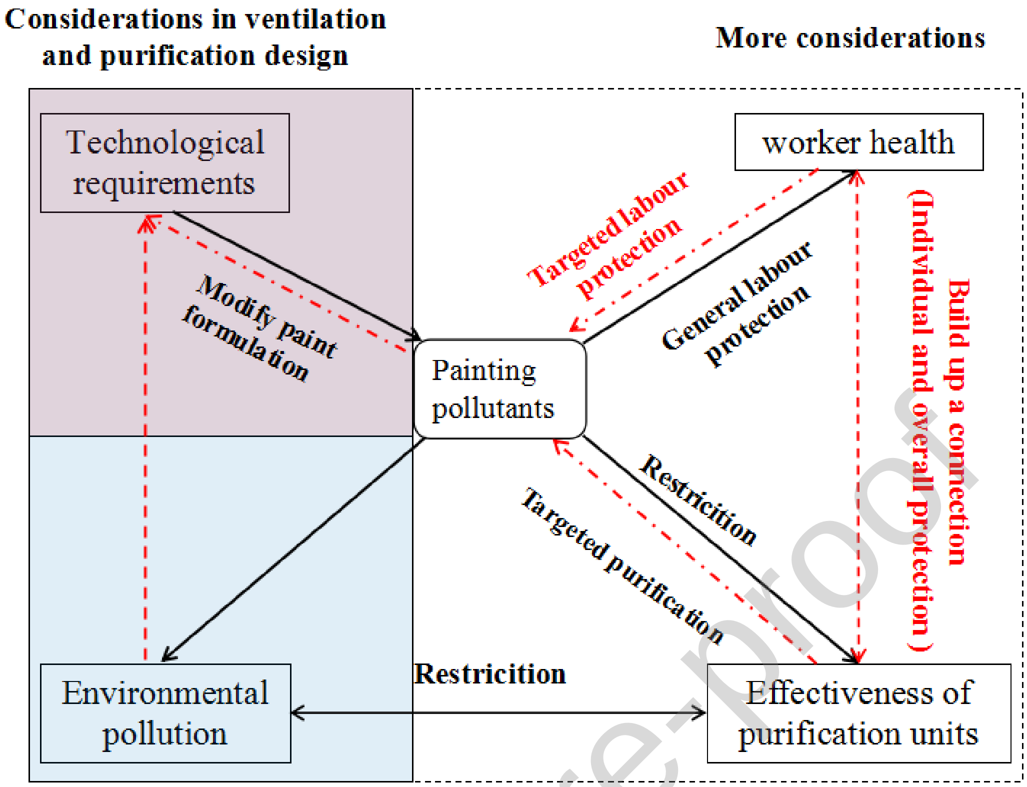

Fig. 10 Relationship between paint industry ventilation design and paint pollution

Table 1: Comparison of VOCs components concentration in varnish spraying and finish spraying

Varnish		**Finish**	
Species	**Mean ± SD (mg/m^3)**	**Species**	**Mean ± SD (mg/m^3)**
Acetic acid, butyl ester	17.3 ± 0.6	Acetic acid, butyl ester	47.2 ± 4.3
2-Heptanone	6.9 ± 0.4	1-Methoxy-2-propyl acetate	25.1 ± 2.0
Methyl Isobutyl Ketone	4.0 ± 0.3	Toluene	18.2 ± 1.4
Acetylacetone	2.6 ± 2.0	2-Butanone	8.6 ± 0.7
Benzene, 1,2,3-trimethyl-	2.5 ± 0.1	Benzene, 1,2,3-trimethyl-	7.4 ± 0.03
p-Xylene	2.0 ± 0.03	Methyl Isobutyl Ketone	4.1 ± 0.2
Toluene	1.8 ± 0.1	2-Heptanone	2.9 ± 0.5

2-Pentanone, 4-hydroxy-4-methyl-	1.5 ± 0.01	2-Ethyl-oxetane	2.9 ± 0.1
1-Methoxy-2-propyl acetate	1.3 ± 0.08	Ethanol, 2-(2-butoxyethoxy)-, acetate	2.3 ± 0.1
2-Butanone	1.3 ± 0.08	1-Butanol	2.2 ± 0.1

Table 2: Comparison of VOCs components concentration in different painting workshops

Irritant gas					
Species	**AP Min-Max, Mean (mg/m^3)**	**FP Min-Max, Mean (mg/m^3)**	**PP Min-Max, Mean (mg/m^3)**	**AMP Min-Max, Mean (mg/m^3)**	**WP Min-Max, Mean (mg/m^3)**
Acetic acid, butyl ester	26.7-64.7, 41.5	8.1-9.8, 9.0	NA	0.0-26.4, 5.7	6.6-15.3, 10.4
1-Methoxy-2-propyl acetate	12.1-52.8, 22.8	NA	NA	NA	NA
Toluene	10.8-27.4, 15.2	27.0-49.1, 39.8	0.1-7.8, 3.7	0.0-20.3, 5.8	0.0-23.6, 8.1
1-Butanol	1.1-82.5, 9.2	NA	NA	NA	NA
Methyl Isobutyl Ketone	1.1-63.0, 8.5	NA	NA	0.0-3.0, 0.6	NA
2-Butanone	4.7-26.8, 8.3	8.9-18.6, 13.8	NA	0.0-11.3, 2.4	0.0-3.3, 1.1
Benzene, 1,2,3-trimethyl-	3.4-12.7, 6.3	NA	NA	NA	NA
2-Heptanone	1.6-18.1, 3.9	NA	NA	NA	NA
Isopropyl Alcohol	1.5-8.5, 2.5	NA	NA	0.0-32.1, 4.6	NA
Ethanol, 2-(2-butoxyethoxy)-, acetate	1.4-7.2, 2.5	NA	NA	NA	NA
Acetylacetone	0.3-3.4, 1.4	NA	NA	NA	NA
Ethyl benzene	0.2-6.0, 0.8	NA	0.0-0.1, 0.0	0.0-10.0, 2.8	6.4-11.1, 9.5
Heptane	0.1-0.4, 0.2	13.0-42.9, 23.7	0.0-0.1, 0.0	0.0-6.7, 1.0	NA
Carbon Tetrachloride	0.01-0.3, 0.1	NA	NA	NA	NA
Cyclohexane, methyl-	0.0-0.3, 0.1	NA	NA	NA	NA

Heptane, 2-methyl-	0.1-0.4, 0.1	NA	NA	NA	NA
Trichloromethane	0.03-1.2, 0.1	NA	NA	NA	NA
o-Xylene	0.02-0.1, 0.04	NA	NA	0.0-6.1, 1.3	0.0-13.4, 4.5
Isobutyl acetate	0.0-0.0, 0.0	NA	NA	NA	NA

Explosive gas

Species	**AP Min-Max, Mean (mg/m^3)**	**FP Min-Max, Mean (mg/m^3)**	**PP Min-Max, Mean (mg/m^3)**	**AMP Min-Max, Mean (mg/m^3)**	**WP Min-Max, Mean (mg/m^3)**
Acetic acid, butyl ester	26.7-64.7, 41.5	8.1-9.8, 9.0	NA	0.0-26.4, 5.7	6.6-15.3, 10.4
Toluene	10.8-27.4, 15.2	27.0-49.1, 39.8	0.1-7.8, 3.7	0.0-20.3, 5.8	0.0-23.6, 8.1
Methyl Isobutyl Ketone	1.1-63.0, 8.5	NA	NA	0.0-3.0, 0.6	NA
2-Butanone	4.7-26.8, 8.3	8.9-18.6, 13.8	NA	0.0-11.3, 2.4	0.0-3.3, 1.1
2-Heptanone	1.6-18.1, 3.9	NA	NA	NA	NA
Isopropyl Alcohol	1.5-8.5, 2.5	NA	NA	0.0-32.1, 4.6	NA
Ethanol, 2-(2-butoxyethoxy)-, acetate	1.4-7.2, 2.5	NA	NA	NA	NA
Benzene, 1,2,4,5-tetramethyl-	0.1-12.5, 1.7	NA	NA	NA	NA
p-Xylene	0.03-1.3, 0.7	NA	NA	0.0-4.1, 0.6	0.0-10.2, 3.4
Heptane	0.1-0.4, 0.2	13.0-43.9, 23.7	0.0-0.1, 0.0	0.0-6.7, 1.0	NA
o-Xylene	0.02-0.1, 0.04	NA	NA	0.0-6.1, 1.3	0.0-13.4, 4.5
Isobutyl acetate	0.0-0.0, 0.0	NA	NA	NA	NA

Carcinogenic gas

Species	**AP Min-Max, Mean (mg/m^3)**	**FP Min-Max, Mean (mg/m^3)**	**PP Min-Max, Mean (mg/m^3)**	**AMP Min-Max, Mean (mg/m^3)**	**WP Min-Max, Mean (mg/m^3)**
Acetic acid, butyl ester	26.7-64.7, 41.5	8.1-9.8, 9.0	NA	0.0-26.4, 5.7	6.6-15.3, 10.4
Toluene	10.8-27.4, 15.2	27.0-49.1, 39.8	0.1-7.8, 3.7	0.0-20.3, 5.8	0.0-23.6, 8.1
Ethyl benzene	0.2-6.0, 0.8	NA	0.0-0.1, 0.0	0.0-10.0, 2.8	6.4-11.1, 9.5

p-Xylene	0.03-1.3, 0.7	NA	NA	0.0-4.1, 0.6	0.0-10.2, 3.4
Naphthalene	0.06-1.4, 0.2	NA	NA	NA	NA
Trichloromethane	0.03-1.2, 0.1	NA	NA	NA	NA
o-Xylene	0.02-0.1, 0.04	NA	NA	0.0-6.1, 1.3	0.0-13.4, 4.5

Note: AP: aircraft painting (data source: this study); FP: footwear painting (data source: (Estevan et al. 2012)); PP: print painting (data source: (Gioda et al. 2002)); AMP: automobile painting (data source: (Ma et al. 2016); (Wang et al. 2013)); WP: wooden furniture painting (data source: (Tong et al. 2019); (Wang et al. 2013))

Table 3: Concentration and risk level of each component in the aircraft painting workshop

Component	**Min-Max, Mean (mg/m3)**	**OEL-TWA**	**OEL-STEL**	**Class**
Acetic acid, butyl ester	26.7-64.7, 41.5	200	300	II
Toluene	10.8-27.4, 15.2	50	100	II
1-Butanol	1.1-82.5, 9.2	100	/	I
2-Butanone	4.7-26.8, 8.3	300	600	I
Isopropyl alcohol (IPA)	1.5-8.5, 2.5	350	700	I
Ethyl benzene	0.2-6.0, 0.8	100	150	I
p-Xylene	0.03-1.3, 0.7	50	100	I
Tetrahydrofuran	0.06-28, 0.3	300	/	I
Naphthalene	0.06-1.4, 0.2	50	75	I
Heptane	0.1-0.4, 0.2	500	1000	I
Carbon Tetrachloride	0.01-0.3, 0.1	15	25	I
Trichloromethane	0.03-1.2, 0.1	20	/	I
Cyclohexane	0.02-0.6, 0.07	250	/	I
o-Xylene	0.02-0.1, 0.04	50	100	I

Author contribution:

Lei Zhao: Drafting the manuscript, acquisition of data, analysis and interpretation of data

Junjie Liu: Revising the manuscript critically for important intellectual content, design of study

Yihui Yin: Drafting the manuscript, data analysis

Jingjing Pei: Interpretation of data, manuscript revision

Wu Xiao and Haiqiao Zhang: Conception and design of study, interpretation of data

Shen Wei: Manuscript review

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: