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Field Study

Occupational Exposure to Volatile Organic Compounds and Mitigation by Push-Pull Local Exhaust Ventilation in Printing Plants

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Abstract: Occupational Exposure to Volatile Organic Compounds and Mitigation by Local Exhaust Ventilation in Printing Plants: Michael K.H. LEUNG *et al.* The University of Hong Kong, Hong Kong—The extensive use of multiple organic solvents in offset lithographic printing causing high emissions of volatile organic compounds (VOCs) indeed poses a serious risk to printing workers' health. In this study, indoor air quality (IAQ) assessments were carried out in seven printing plants and the main objectives were to understand the effect of VOC emissions on IAQ and develop effective mitigation measures to protect workers. The thorough gas chromatography/mass spectrometry (GC/MS) measurements showed that although a variety of VOCs were presented in the indoor air, none of them was found close to individual 8-h time-weighted average (TWA) of the occupational exposure limit (OEL). The additive effect was also found below the critical value of unity. However, short-term personal exposure to total volatile organic compounds (TVOCs) was exceedingly high when a print worker carried out blanket and ink roller cleaning procedures. Therefore, the occupational health risk was mainly due to repeated short-term exposures during intermittent VOC-emitting procedures rather than long-term exposure to background VOCs. Push-pull local exhaust ventilation (LEV) was identified as an effective mitigation measure. Computational fluid dynamics (CFD) analysis was conducted to study the push-pull LEV operation. It was found that there existed a threshold LEV air flow rate for an abrupt reduction in the worker's exposure to VOCs. The reduction was less sensitive when the LEV airflow was further increased beyond the threshold. These phenomena, consistent with experimental results reported by other investigators, were explained by detailed CFD analysis showing the competition between the general ventilation and the push-pull LEV to become the dominating driving force for the resultant local flow pattern.
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Key words: Volatile organic compounds (VOCs), Printing, Gas chromatography/mass spectrometry (GC/MS), Push-pull local exhaust ventilation (LEV), Computational fluid dynamics (CFD)

In the printing industry, the main sources of volatile organic compounds (VOCs) in commercial offset lithography are the uses of organic solvents, inks, fountain solutions, and cleaning agents[1, 2]. Considerable amounts of vaporized toluene, xylenes, alcohols, and other airborne organic compounds are emitted to the indoor air. The chemical vapor composition highly depends on the type of printing press and paper substrate used. In a sheet-fed press and a non-heat-set web press, the inks are dried by means of oxidative polymerization and absorption into the substrate, respectively, with low emissions to the indoor environment. However, in a heat-set web press, the inks are dried by evaporating aliphatic ink oils causing significant amounts of emissions[3]. Other printing processes and operations that may cause serious VOC emissions include proofing, ink mixing, cleaning, binding, laminating, and chemical storage. Previous studies have reported the measurements of occupational exposure to various airborne organic solvents during the offset printing press operations[2–4]. Evidence has also indicated a close relationship between occupational VOC exposure and consequential adverse health effects on workers in the printing industry in Hong Kong, China[5, 6] and in other countries[2, 7–10]. The adverse health effects include impairment of color vision, liver dysfunction, hyperglycemia, some neurological symptoms, and cancers. Further investigation is needed to analyze the air quality for a better understanding of the occupational exposure. Effective mitigation measures can then be

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Table 1. Descriptions of printing plants and sampling points

Plant index	Plant size*	Sampling point(s)	Area covered (m^2)	Type and number of printing equipments
I	Small	1	150	• 3 single-color sheet-fed offset printing presses • 4 photocopiers
II	Small	2	150	• 2 four-color sheet-fed offset printing presses
III	Small	3	300	• 3 four-color sheet-fed offset printing presses
IV	Medium	4	300	• 3 four-color sheet-fed offset printing presses
V	Large	5, 6	3,000	• 6 four-color web-fed offset printing presses • 8 four-color sheet-fed offset printing presses
VI	Large	7, 8	1,000	• 4 four-color web-fed offset printing presses • 4 four-color sheet-fed offset printing presses
VII	Large	9, 10	2,000	• 4 four-color web-fed offset printing presses

*Plant size was classified by the total number of print workers: small (10 to 20), medium (21 to 100), large (101 to 300). Note: All printing plants were equipped with a general ventilation system with ceiling supply and return air ducts.

identified and recommended.

In this study, the first objective was to evaluate the occupational VOC exposure, quantitatively, by detailed field measurements. The second objective was to conduct a parametric analysis on a proposed mitigation measure, push-pull local exhaust ventilation (LEV)[11, 12]. Computational fluid dynamics (CFD) were employed to simulate the flow of VOCs with the presence of push-pull LEV. The detailed findings of this study are presented in this paper.

Materials and Methods

1. Field measurements of VOC exposure

In order to obtain the details of occupational VOC exposure in the printing industry, field measurements and analyses were conducted. Seven printing plants with a total of ten sampling points were specifically selected to cover a variety of plant sizes and printing press types as described in Table 1. The plant size was classified by the total number of print workers. Small, medium, and large sizes refer to 10 to 20, 21 to 100, and 101 to 300 workers, respectively. For the whole spectrum from small to large printing plants, production covered a variety of products including business cards, pamphlets, posters, brochures, books, magazines, and newspapers. All the sampling sites were air-conditioned and ventilated by conventional ceiling supply and return air-duct systems, designed for 5 to 12 air changes per hour (ACH). The printing plants selected should serve as a reasonable sampling set representing the printing industry in Hong Kong.

The sampling points for 8-h TWA tests were identified based on the following criteria: (i) candidate locations were the ones normally occupied by employees, such as workers' stations and (ii) among the candidate locations, the one having the highest TVOC concentration identified by a portable TVOC monitor (RAE Model PGM-30 TOXIRAE Photo Ionization Detector calibrated by isobutylene) was selected to represent the worst case scenario.

In each air sampling, an evacuated passivated stainless steel canister was used to collect an 8-h air sample during the normal operating hours. After the sampling was completed, the canister was immediately sent to a laboratory, certified by the Hong Kong Laboratory Accreditation Scheme, for gas chromatography/mass spectrometry (GC/MS) analysis according to the USEPA TO-15 Method[13]. The first step of the analysis was to concentrate the VOC contents in a multisorbent concentrator equipped in an Entech Instruments Concentration System Model 7100. The concentrated sample was then dried by purging the concentrator with helium. Then, the sample was released by thermal desorption and collected in a gas chromatographic column. An HP 5890 Series II Gas Chromatograph and an HP 5972 Series Mass Selective Detector were used to determine the mass spectra for individual peaks in the total ion chromatogram. The HP 5972 was a quadrupole mass filter that either scanned continuously a wide range of mass to charge ratios (SCAN mode) or monitored the ion on the target list (SIM mode). The mass spectra for individual peaks in the total ion chromatogram represented the fragmentation pattern of ions which actually determined the composition of the VOCs. The fragmentation pattern and intensity of the ions were compared with an in-house calibrated standard to determine the quality and quantity of the VOCs, respectively.

In these measurements, the VOC targets included 37 airborne organic contaminants commonly found in industrial facilities, such as toluene, methylene chloride, xylenes, benzenes, and others as listed in Table 2. The

Table 2. GC/MS analysis for 8–h TWA VOC exposure and recommended OEL

No.	Substance	Airborne concentration at sampling point (ppb)										OEL* (ppb)
		1	2	3	4	5	6	7	8	9	10	
1	Benzene	–	–	4.9	–	–	–	12	–	11	9	500
2	Bromoethane	–	–	–	–	–	–	–	–	–	–	–
3	Carbon tetrachloride	–	–	–	–	–	–	–	–	–	–	5,000
4	Chlorobenzene	1.9	–	–	–	–	–	–	–	–	–	10,000
5	Chloroethane	–	–	–	–	–	–	–	–	–	–	–
6	Chloroform	4.7	–	11	–	–	–	23	1.7	1.0	3.4	10,000
7	Chloromethane	2.2	–	–	–	–	–	3.0	2.1	2.0	1.3	50,000
8	1,2–Dibromoethane	–	–	–	–	–	–	–	–	–	–	–
9	m–Dichlorobenzene	–	–	–	–	–	–	–	–	–	–	25,000
10	o–Dichlorobenzene	–	–	–	–	–	–	–	–	–	–	25,000
11	p–Dichlorobenzene	–	–	–	–	–	–	1.2	1.6	5.6	–	10,000
12	Dichlorodifluoromethane	1.6	–	2.2	–	2.6	1.5	–	–	1.5	–	1,000,000
13	1,1–Dichloroethane	–	–	–	–	–	–	–	–	–	–	100,000
14	1,2–Dichloroethane	–	–	–	–	–	–	–	9.3	–	–	10,000
15	1,1–Dichloroethene	–	–	–	–	–	–	–	–	–	–	–
16	cis–1, 2–Dichloroethene	1.3	–	–	–	–	–	1.3	1.4	1.6	–	10,000
17	1,2–Dichloropropane	–	–	–	–	–	–	–	–	–	–	–
18	cis–1,3–Dichloropropene	–	–	–	–	–	–	–	–	–	–	–
19	trans–1,3–Dichloropropene	–	–	–	–	–	–	–	–	–	–	–
20	1,2–Dichloro–1,1,2,2–Tetra –chloroethane	–	–	–	–	–	–	–	–	–	–	–
21	Ethylbenzene	39	26	10	14	3.4	14	67	45	39	22	100,000
22	Methylene chloride	18	2.5	61	4.8	8.6	3.6	380	7.5	10	31	50,000
23	Styrene	7.1	–	–	–	1.4	–	5.0	1.8	1.9	1.5	20,000
24	1,1,2,2–Tetrachloroethane	–	15	–	–	–	–	–	–	–	–	1,000
25	Tetrachloroethylene	–	–	–	–	–	–	3.7	–	–	1.5	25,000
26	Toluene	280	1,000	1,200	1,900	26	930	2,000	3,900	900	830	50,000
27	1,1,1–Trichloroethane	7.8	–	–	–	–	–	1.8	1.5	–	–	350,000
28	1,1,2–Trichloroethane	–	–	–	–	–	–	–	–	–	–	10,000
29	Trichloroethylene	–	–	14	–	–	–	–	–	–	–	50,000
30	Trichlorofluoromethane	–	–	–	–	–	–	1.8	–	1.4	1.2	–
31	1,1,2–Trichloro– 1,2,2 –Trifluoroethane	–	–	–	–	–	–	–	–	1.2	–	1,000,000
32	1,2,4–Trimethylbenzene	–	–	27	400	11	22	64	200	82	110	25,000
33	1,3,5–Trimethylbenzene	22	43	6.2	96	3.9	8.1	15	39	20	18	25,000
34	Vinyl chloride	–	–	–	–	–	–	–	–	1.4	–	1,000
35	m–Xylene	51	43	23	27	11	26	77	60	68	54	100,000
36	o–Xylene	18	17	10	65	4.6	10	34	24	32	26	100,000
37	p–Xylene	51	43	23	27	11	26	77	60	68	54	100,000

Note: Dash (–) represents the concentration below the threshold detectable limit of 0.1 ppb or OEL value not available.
* 8–h TWA OEL recommended by the Labour Department of the Hong Kong Government (2002)

adverse health effects due to the exposure to a single organic substance and a mixture of substances were determined by the individual effect (IE_i) and the additive effect (AE), respectively, expressed by

$$IE_i = \frac{C_i}{OEL_i} \quad (1)$$

and

$$AE = \sum_i IE_i = \sum_i \frac{C_i}{OEI_i} \quad (2)$$

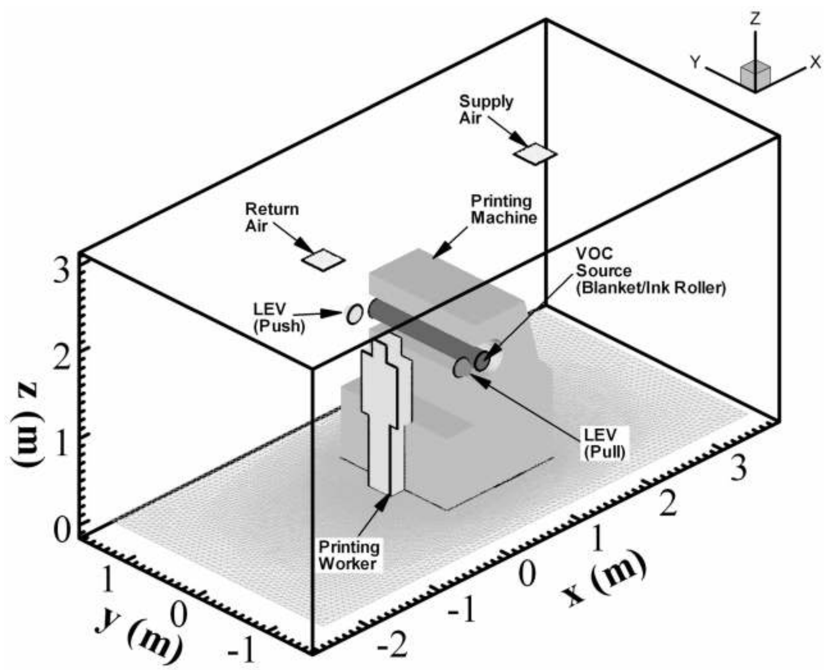

Fig. 1. CFD modeling domain of push-pull LEV for printer blanket and ink roller cleaning.

where C_i and OEL_i are the airborne concentration of chemical substance i and its 8-h TWA occupational exposure limit, respectively.

In addition to the air sampling for 8-h TWA VOC exposure, real-time sampling of TVOC was conducted for the short-term personal exposure of a worker performing the critical blanket cleaning procedure. A TVOC monitor was placed in the worker's breathing zone that was a 300-mm hemisphere extending in front of the face. The instantaneous readings were recorded as the worker cleaned the blanket cylinder of a small single-color sheet-fed offset printing press. The cleaning agent used was the common varnish makers' and painters' (VM & P) naphtha.

2. CFD analysis of push-pull LEV

The above 8-h TWA and short-term personal exposure measurements were analyzed to gain a better understanding of the VOC dispersion and to support the recommendation of push-pull local exhaust ventilation (LEV) as an effective mitigation measure to manage the emissions. The performance of push-pull LEV was evaluated by computational fluid dynamics (CFD) analysis for thorough numerical tests of the pollutant transport behaviors. The problem domain, as illustrated in Fig. 1, consisted of a VOC emitting blanket or ink roller, a printing worker performing the cleaning procedures, and a push-pull LEV device. The height of the printing worker was 1.73 m. The head was modeled by a cube with each side being 0.2 m long and the shoulders were 0.5 m wide. The roller, represented by a horizontal cylinder, had a diameter and a length of 0.2 m and 1.5 m, respectively. The separation between roller and the printing worker's face was 0.4 m. The supply and extraction hoods of the push-pull LEV device were aligned midway between the printing worker and the roller. The printing room sized 6 m × 3 m × 3 m, equal to 54 m^3, was ventilated by a conventional ceiling supply and return air-duct system. The general ventilation rate was fixed at 5 ACH, equivalent to a supply air flow rate of 0.075 m^3s^{-1} and a corresponding air speed of 0.83 ms^{-1} at the supply air grille. The same amount of air was extracted from the return air grille. The push-pull LEV supply air and exhaust air were set equal to each other.

In this CFD model, the turbulent airflow was assumed to be steady-state, but the VOC dispersion was in a transient mode. The mathematical fluid dynamic model consisted of the Navier-Stokes and continuity equations in an ensemble-average format. The turbulence was modeled by the standard two-equation k-ε model. The transient VOC dispersion was determined by the discrete particle transport model and the VOC exposure was quantified in terms of "susceptibility" defined as the percentage of the emitted VOCs actually flowing through the breathing zone of the worker.

In the computation, the problem domain was discretized into 1,620,000 unstructured tetrahedral elements by the mesh generator GAMBIT 2.0. The commercial CFD code Fluent 6.1[14] was employed to implement the finite volume method to set up the governing equations in algebraic form. The massive algebraic equations were numerically solved for the nodal solutions converging to a dimensionless residual less than 0.001.

Results and Discussion

1. GC/MS analysis

The results of the GC/MS analysis are summarized in Table 2. The VOC concentration is presented in terms of parts per billion (ppb) by volume. To facilitate identification of any exceedingly high concentrations, Table 2 also presents the 8-h TWA OEL values recommended by the Hong Kong Labour Department[15]. The Hong Kong OEL values are comparable to the NIOSH guidelines[16] and the OSHA standards[17]. A dash sign (–) represents either a measured concentration below the threshold detection limit of 0.1 ppb or the OEL value not available.

Among the 37 VOCs tested, ethylbenzene, methylene chloride, toluene, 1,3,5-trimethylbenzene, m-xylene, o-xylene, and p-xylene were detected in all the printing plants. At some sampling points, additional organic compounds detected were benzene, chlorobenzene, chloroform, chloromethane, p-dichlorobenzene, dichlorodifluoromethane, 1,2-dichloroethane, cis-1,2-dichloroethene, styrene, 1,1,2,2-tetrachloroethane, tetrachloroethylene, 1,1,1-trichloroethane, trichloroethylene, trichlorofluoromethane, 1,1,2-trichloro-1,2,2-trifluoroethane, and vinyl chloride. The magnitudes of the measurements were consistent with values already reported in the literature[2, 3].

Toluene was the dominating VOC found in the air at a relatively high concentration up to 3,900 ppb. Toluene also contributed to high individual effect (*IE*) and high additive effect (*AE*). The maximum values of *IE* and *AE* calculated based on the Hong Kong OEL were 0.078 and 0.091, respectively, both found at Sampling Point 8. The additive effect was lower than the critical value of unity by one order of magnitude. The GC/MS analysis omitted some important chemicals, such as n-hexane and isopropyl alcohol. However, their inclusion might not increase the additive effect by a significant amount based on the relative weightings of n-hexane, isopropyl alcohol, and toluene measurements in printing plants[5]. The above results show that the apparent adverse occupational health effects in the printing industry might not result from continuous exposure to the 8-h TWA level of VOCs.

2. Real-time sampling

The study further investigated the short-term personal exposure to high concentration of VOCs on printing workers. Blanket cleaning and ink roller cleaning are often the most critical procedures that yield high short-term VOC exposure. In each test, the concentration of TVOCs was measured by a TVOC monitor in the breathing zone 300 mm away from the face of a printing worker while he was performing the blanket cleaning procedure for a small single-color offset printing press. The TVOC measurements in parts per million (ppm) by volume are plotted in Fig. 2. In trial 1 before the cleaning (0 to 30 s), the average TVOC concentration was 23 ppm. It was higher than the 8-h TWA values reported in Table 2 because the TVOC measurements were collected near the emission source. After the worker started the cleaning process, the TVOC level quickly climbed up to a maximum of 486 ppm in less than 10 s. In the middle of the cleaning process (at 40 s), the TVOC measurements started to decline as the liquid cleaning agent was mostly vaporized from the blanket. After the worker finished the cleaning procedures (after 50 s), the TVOC concentration gradually reduced to 40 ppm, a level in a magnitude similar to the initial condition. A second peak was recorded thereafter (around 70 s) possibly due to the VOCs vaporized from the cleaning rag placed besides the printing press and exposed to the ambient after use. Trial 2 also exhibited a similar TVOC variation as plotted in Fig. 2. The lower peak occurring at 16 s was due to the interference of opening and closing the bottle of the cleaning agent. More tests were conducted and the maximum peak readings were between 350 and 1,100 ppm.

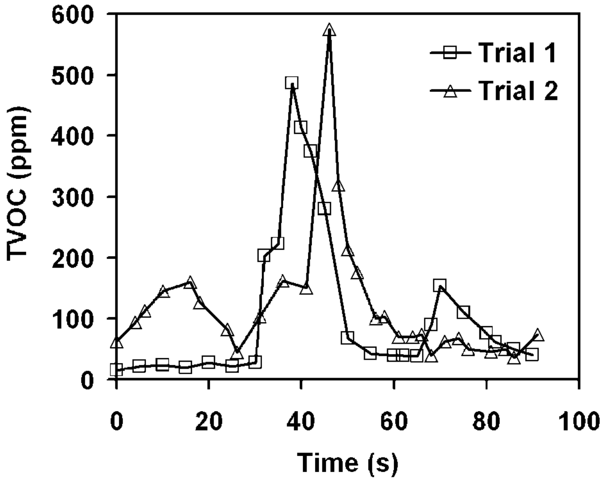

Fig. 2. TVOC measurements during blanket cleaning for a small one-color offset printing press.

During the cleaning process, the majority VOC detected by the TVOC monitor would be the cleaning agent, VM & P naphtha. Thus, the TVOC readings could be converted to the concentration of VM & P naphtha by a multiplying correction factor, which was equal to 1 as provided by the TVOC monitor manufacturer (RAE Systems). Accordingly, the peak TVOC reading of 486 ppm, shown in Fig. 2, was equivalent to 486 ppm of VM

& P naphtha. The exposure time for high TVOCs was short (about 20 s) for cleaning the blanket cylinder of a small offset printing press. In practice, a worker may carry out the cleaning procedures for sizable four-color offset printing presses. The exposure time will increase accordingly to the order of 10 min. Therefore, it is reasonable to compare the peak reading with the 15-min short-term exposure limit (STEL[15]). The measured VM & P naphtha concentration equal to 486 ppm exceeded the STEL value of 400 ppm. The results imply that over an extended period of time, repeated short-term exposure to high VOC concentration during the cleaning procedures is the main cause of occupational health problems in the print industry.

3. Push-pull LEV

From the GC/MS results, the low 8-h TWA exposure indicates that the existing general ventilation systems are providing adequate air changes to dilute the VOCs generated by the printing machinery and processes. The main problem is most likely the high short-term VOC exposure, locally, near the source during the cleaning procedure as shown by the real-time TVOC measurements exceeding the STEL level. Increasing the air change rate of the general ventilation may slightly lower the local short-term exposure, but the surrounding areas will be over ventilated resulting in energy inefficiency.

Alternatively, the push-pull LEV method[11, 12] is recommended for solving the local VOC problem in blanket and ink roller cleaning. A push-pull LEV system consists of a supply air hood and an exhaust air hood that can induce a local airflow path: supply hood → contaminant source (blanket and ink roller) → exhaust hood. The main objective is to divert the VOC emissions away from the worker. It is not necessary to collect and remove all the emissions by the LEV exhaust hood because the existing general ventilation can perform subsequent dilution effectively. For a given level of protection, the required exhaust air flow rate of a push-pull LEV system is lower than that of a conventional LEV system. Therefore, push-pull LEV causes less interference to the airflow in the surrounding indoor environment.

The performance of push-pull LEV in a printing plant was evaluated by CFD analysis. For each test condition, the transport of VOCs was modeled by 1,000 particle trajectories. As shown in Fig. 3, without the use of LEV, the VOCs emitted from the source are carried by the general ventilation towards the return air grille. In the worst scenario, a worker standing in the flow field of VOCs is exposed to exceedingly high concentration. In this modeling case, the susceptibility of the worker to the VOC emissions is 36%.

The susceptibility (S) as a function of the push-pull LEV air flow rate (q) is presented in Fig. 4. It is observed that when q is small (<0.048 m^3s^{-1}), an increase in q causes a slight decrease in S. As q further increases and exceeds a threshold of 0.07 m^3s^{-1}, S decreases abruptly to 7%. Increasing q beyond the threshold causes a less sensitive reduction in S. These observations are consistent with the experimental measurements reported by Ojima[12]. The VOC exposure behavior can be explained by the local airflow pattern resulting from the combination of both general ventilation and push-pull LEV. Comparing Fig. 5 with Fig. 3, a low q causes an interference to the flow field but many path lines still pass around the worker's head. The susceptibility is reduced but the magnitude is insignificant. The susceptibility is still high even when q is increased to 0.048 m^3s^{-1} as shown in Fig. 6. When

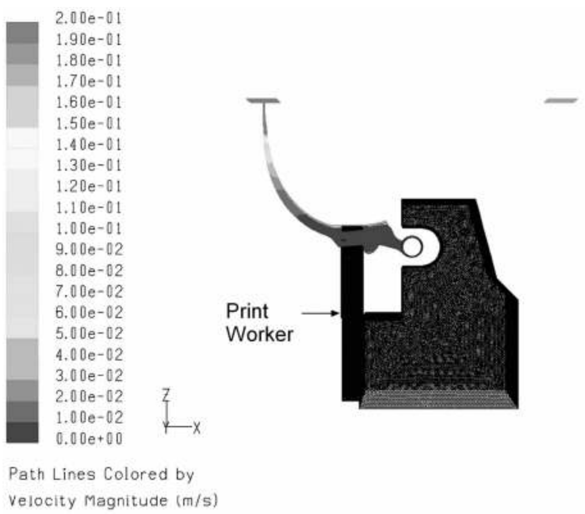

Fig. 3. Flow field without operation of push-pull LEV.

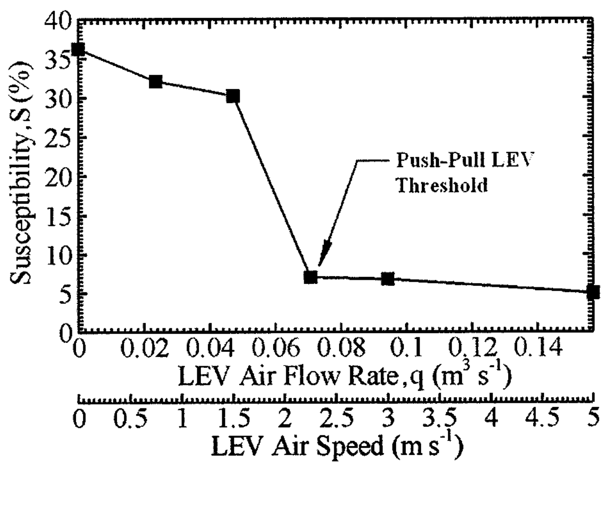

Fig. 4. Susceptibility of worker to VOC emissions versus push-pull LEV flow rate.

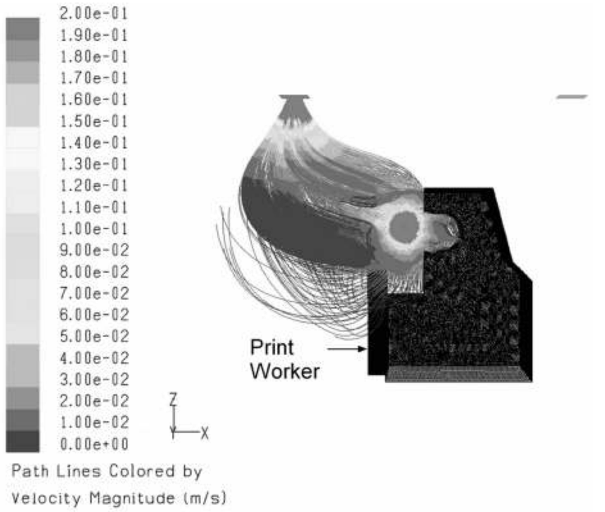

Fig. 5. Flow field with push-pull LEV operating at 0.024 m^3s^{-1} (U = 0.75 m s^{-1}).

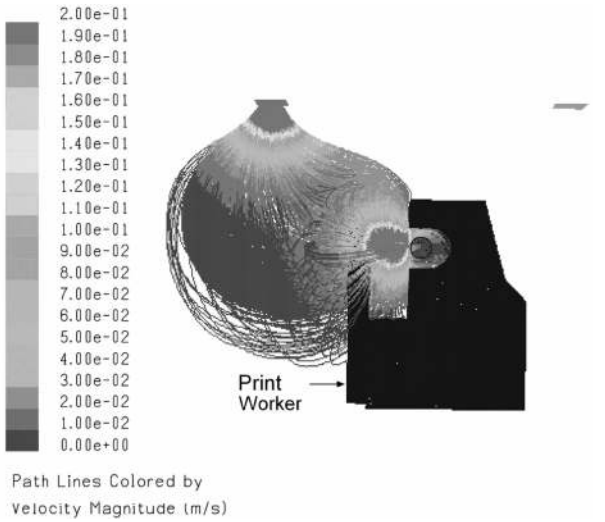

Fig. 6. Flow field with push-pull LEV operating at 0.048 m^3s^{-1} (U = 1.5 m s^{-1}).

the push-pull LEV air flow rate is increased to the threshold of 0.07 m^3s^{-1} as shown in Fig. 7, the change in the flow field is considerable as the LEV becomes the dominating effect. The path lines show no direct transport of the emissions from the source to the worker's head. The CFD data analysis shows that 64% of the path lines merge together and directly go to the exhaust of the LEV. The remaining 36% of path lines represent dispersion to the surrounds. After the new flow field is fully established, further increase in the LEV air flow rate beyond the threshold value yields minor reduction in the VOC exposure.

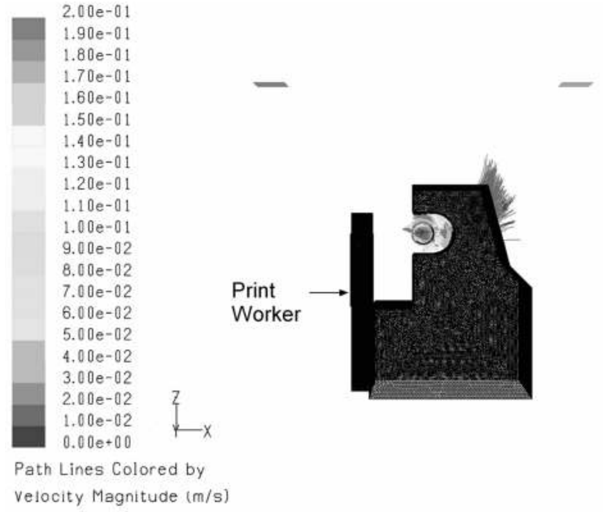

Fig. 7. Flow field with push-pull LEV operating at 0.07 m^3s^{-1} (U = 2.25 m s^{-1}).

Conclusions

In response to the adverse health effects due to exposure to airborne VOCs in the printing industry, an investigation was conducted to study VOC emissions and transport behavior in the working environment. From the field measurements, it was found that the 8-h TWA additive effect was consistently lower than unity. Therefore, the health risk might not be due to 8-h exposure to background VOCs five working days a week. On the other hand, it was found that a printing worker was exposed to high VOCs exceeding the STEL level when he carried out cleaning procedures. Over an extended period of time, the repeated short-term personal exposure to high VOC concentration would be the probable cause of adverse occupational health effects.

Using a push-pull local exhaust ventilation to divert VOC emissions away from print workers has been identified as a promising method for protecting their health. The CFD analysis conducted shows the characteristics and performance of a push-pull LEV operation in a printing plant. There exists a threshold LEV air flow rate for effective reduction of the worker's exposure to VOC. Therefore, proper design and control of a push-pull LEV system should ensure its operation beyond the threshold. These findings are also applicable to the use of push-pull LEV for enhancing occupational health in other similar industrial processes with local emissions, such as welding, soldering, grinding, machining, and laboratory testing, among others.

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