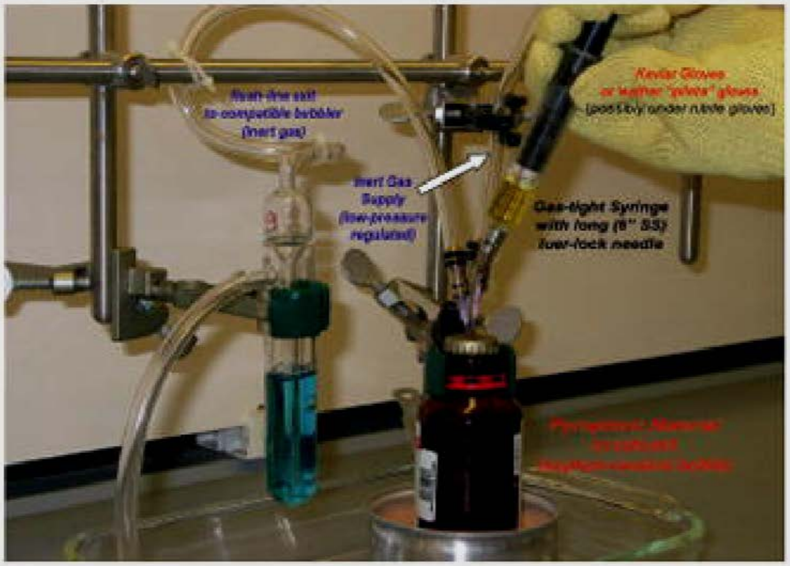
SEPTEMHERIOCTOBER 2000
Volume 16, Number 5

Journal of CHEMICAL Health & Safety

Laboratory Ventilation

Design and Operation



Hazard, risk and pyrophorics, p. 51

PUBLISHED BY ELSEVIER INC. FOR THE ACS DIVISION OF CHEMICAL HEALTH AND SAFETY

1871-5532/$36.00
doi:10.1016/j.jchas.2009.07.001

Division of Chemical Health and Safety of the American Chemical Society
Published by Elsevier Inc.

The technology for laboratory Indoor Air Quality (IAQ) has advanced significantly since the late 1800s. The industrial revolution spawned one-room chemistry laboratories that were ventilated using transoms, sky lights and open windows. The laboratories were built with little regard for occupant health and safety. The available knowledge and technology to improve the IAQ conditions was limited and there were no regulations to provide standardization. Technological advancement and innovation depends on a combination of trial and error and scientist/engineer cooperation. A higher than average frequency of illness and death caused by exposure to toxic vapors, air borne particles and radioactive materials in poorly ventilated spaces heightened awareness of health and safety concerns and led to the development of the fume hood. The design philosophy was to maximize containment of hazardous materials and vapors. However, there was no statistical correlation between long-term chemical exposures and human health until the late 20th century.

Early laboratory containment ventilation air flow systems (1940s) depended only upon the operation of a hood exhaust fan for power. This system ‘‘pulled’’ outside air through the lab into the fume hood to the exhaust duct work and through the exhaust fan to be discharged outside the building. The system was neither equipped to provide conditioned air nor capable of ‘‘pushing’’ air into the laboratory. Refrigerated air systems to address occupant comfort appeared in laboratory buildings in the 1950s. But the technology did not yet exist to mechanically control room supply and room exhaust via the hood sash opening.

Constant volume supply and exhaust air flow systems were designed to mechanically control hood face velocity based on the hood sash opening and/or a bypass opening above the hood sash. Constant velocity across the sash could not be effectively achieved with this design because air flow across the sash opening was compromised by a combination of external factors including room air currents, location of the hood and chemicals and equipment stored in the hood.

In the latter half of the 20th century, opinion differed regarding the practice of containment ventilation versus dilution ventilation. Dilution ventilation could be achieved relatively inexpensively based on the premise that the more air changes per hour (ACH) pushed through the lab and exhausted outside, the safer and cleaner the IAQ. Containment ventilation, specifically designed to keep hazardous materials within fume hoods, was expensive and difficult to achieve because of the inherent design problems with multiple fume hoods, architectural and mechanical design features used in the facility and potential health effects of chemical exposure to poorly understood reagents. Although a one-size-fits-all approach was not the answer to a safe and comfortable laboratory environment, cost factors often dictated ventilation strategies without regard to laboratory performance or IAQ improvement. Frequently a dilution ventilation approach was applied to the lab design when a containment approach would have been a safer alternative.

Today extensive data is being collected, analyzed and used to develop standards for laboratory ventilation. Results from empirical and numerical studies using computational fluid dynamics (CFD) technology have been incorporated into national and international standards such as the American National Standard Institutes (ANSI)-Z9.5, Laboratory Ventilation, the 1999 and 2003 American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE)-Application Handbook, and the ASHRAE Fundamentals Handbook.

Based on current data, laboratory practices and technologies that use reduced quantities of chemicals, the minimum recommended ACH is being revisited to consider energy conservation strategies that reduce cost and ‘green house’ emissions. There is strong evidence indicating that a higher ACH does not necessarily improve IAQ. One approach to laboratory ventilation design is to consider ‘point’ or ‘source’ containment strategies that use sensors to detect and control air flow.

In this collection of publications the authors review current trends in IAQ health and safety in laboratories. They provide recent data that supports revisiting the use of typical ACH in all laboratory scenarios and they propose strategies and tools to apply new ACH concepts to labs in the 21st century.

Geoffrey Bell, B.S.M.E., M. Arch. of Lawrence Berkeley National Laboratory, presents the notion that typical ventilation design practice, although ubiquitous in the industry, is insufficient to optimize safety or energy efficiency. A step-wise process is described to develop a safe and energy efficient ventilation rate that takes the laboratory mission and its unique variables into account. The design team can optimize ventilation rates by evaluating performance standards under multiple scenarios, ensuring, through the scientific community, that good laboratory practices are in place to maximize the effectiveness of the designed mechanical systems, reviewing occupancy schedules to optimize setback control strategies, and establishing emergency override systems and demand-controlled ventilation to provide real-time variable-air-volume control.

In ‘Specification of Airflow Rates in Laboratories’, Thomas Smith & Sandra Yancey-Smith discuss issues required to evaluate and determine appropriate ventilation guidelines for ensuring safe, productive and energy efficient laboratories. Their premise is that the practice of using typical ACH fails to account for airflow patterns within the room and the factors affecting contaminant accumulation and dilution. Since laboratory conditions change, reliance on a single airflow rate can lead to a false sense of safety and increased energy consumption. Safe, productive and energy efficient laboratories require specifying minimum laboratory airflow rates that ensure proper performance of exposure control devices, provision of comfortable working conditions and training laboratory personnel to recognize laboratory hazards and take appropriate action when required.

Robert Klein et al. of Yale University investigates the relationship between laboratory air quality and ACH rates

1871-5532/$36.00
doi:10.1016/j.jchas.2009.07.001

under controlled releases of organic solvent during simulated routine bench-top work as well as small spills in ''Laboratory Air Quality and Room Ventilation Rates.'' The accumulation, peak concentration, and clearance of airborne contaminants was found to be proportional to the overall room ACH rate, and significantly influenced by chemical vapor pressure and density, room temperature, and the direction and velocity of room air currents. This work reinforces the concept that no single ACH rate is appropriate for all rooms, contaminants, or operations. It also reminds practitioners that ACH rates cannot simply be lowered below original design specifications without consideration of the engineering and safety implications of the change. Based on the results of their study, they suggest that ACH rates above 12 are generally unnecessary while those below 8 warrant careful consideration. Re-engineering of supply and exhaust air diffusers to provide optimal location, number, and style can be an effective means to increase the efficiency of laboratory ventilation systems and potentially allow for designs at lower ACH rates.

Lou DiBerardinis, MS of MIT, in ''Laboratory Air Changes: What is all the Hot Air About?'' suggests that the lack of exposure assessment studies related to air exchange rates and health effects in laboratories makes it difficult to select an ACH rate that protects health. This paper examines the factors that affect ACH exchange rates in laboratory design and presents a practical decision logic for determining acceptable ACH rates based on the proper design of the laboratory for controlling airborne emissions.

Farhad Memarzadeh, P.E., PhD, of the National Institutes of Health has conducted numerous experimental and numerical studies that support innovative approaches to revising IAQ standards in laboratories. In an earlier paper, a CFD modeling approach is used to demonstrate that a slot bench exhaust system can be an effective and energy saving strategy in controlling thermal comfort by remov- ing the heat dissipation on the bench top. In this subsequent case study con- cerning the ventilation requirement in a typical lab with a high cooling load, CFD is used to focus on assessing the impact of this system on indoor air quality. Since procedures involving harmful chemicals are exclusively con- ducted in fume hoods while chemicals used on the bench top are generally safe, the practice of designing to a typical ACH assumes that concentrations fol- lowing emission are uniformly distrib- uted throughout the lab and fails to account for room airflow patterns, laboratory conditions, contaminant quantities and properties. Using typical ACH recommendations may result in higher than predicted contaminant concentrations and exposure may depend on where a person is located within the lab following contaminant emission. By increasing the ACH rate, the potential occupant exposure to contaminants may be increased by air turbulence, contaminant spread and a higher rate of contaminant generation. The results also suggest that contaminant removal effectiveness is not linear with an increase in ACH and that a lower ventilation flow rate can be used without remarkable impact on the air quality in the occupied zone. This study provides numerical justification for the concepts in this collection of publications and supports the principle to design laboratories with lower ACH when thermal comfort and contaminant containment are factored into the design.

The primary objective of laboratory ventilation is to protect the health and safety of personnel and to optimize occupant comfort. Emerging technologies require a scientific and analytical approach for designing efficient and practical ventilation systems. One such technology is demand-controlled ventilation (laboratory DCV) that utilizes pollutant sensors in order to provide real-time variable-air-volume ventila- tion control. Tools such as advanced physical modeling techniques and tra- cer gas simulations combined with practical decision logic for determin- ing acceptable ACH rates for control- ling airborne emissions can help optimize laboratory ventilation rate through innovative design strategies. The importance of incorporating good laboratory practices and sound standard operating procedures in conjunction with the ventilation strategy of choice cannot be understated.

Farhad Memarzadeh
Division of Technical Resources,
National Institutes of Health,
Bldg 13, Rm. 201, 13 South Drive,
MSC 5759, Bethesda,
MD 20892-5759, USA
E-mail address
memarzaf@ors.od.nih.gov

Effect of reducing ventilation rate on indoor air quality and energy cost in laboratories

Numerous Computational Fluid Dynamic (CFD) studies have been performed to support innovative approaches to revising indoor air quality (IAQ) standards in laboratories. In a previous study,[1,17] the author demonstrates that a slot bench exhaust system can be an effective and energy saving strategy to control thermal comfort by removing the heat dissipation on the bench top and that this system has a negligible effect on the containment ability of a fume hood located upstream from the bench. In this subsequent case study concerning the ventilation requirement in a typical lab with a high cooling load, CFD is used to focus on assessing both the IAQ and the cost impact of the bench slot system versus a conventional ventilation system on IAQ when the number of ACH is reduced from the typical 12 ACH to 6 ACH. The ability of the bench slot exhaust system to remove airborne chemicals in the case of a bench top chemical spill is examined at the reduced ACH. This paper provides quantitative justification to support the concept that IAQ is not directly proportional to a reduction in ACH but rather is dependent on a combination of factors including the ventilation system design, the control of local conditions and the use of standard operating procedures specific to the laboratory operations. The results suggest that a lower ventilation flow rate can be used without remarkable impact on the air quality in the occupied zone, whether or not the bench slot exhaust system is employed.

By Farhad Memarzadeh

INTRODUCTION

Indoor air quality improvement in the working space has long been one of the most important subjects of the ventilation system designs.[2,3] The air quality in laboratories, in particular, has a profound effect on occupant health since many chemicals used in laboratories are hazardous to the occupants' health. Exposure to volatile chemicals constitutes one of the top health and safety hazards to laboratory workers. A fume hood is often the primary contaminant control device. Fume hoods are designed to capture and exhaust hazardous contaminants generated inside its enclosure by extracting air from the back of the hood to the outside of the building. Well developed standard operating procedures (SOPs) for the use of flammable and toxic chemicals in the fume hood are essential in the laboratory setting. SOPs reduce the risk of laboratory worker exposure to these hazardous chemicals. Meanwhile, procedures involving non-toxic or low toxic chemicals are often carried out on the bench top. Some chemicals, although non-toxic, may cause physical discomfort of occupants such as skin or eye irritation, unpleasant smell, etc. If these chemicals are spilled accidentally on the bench top, they would evaporate and be dispersed in the room via convection and diffusion mechanisms. Good Laboratory Practice includes SOPs that address the handling of both toxic and non-toxic agents and what to do in case of an accidental spill. By incorporating safety procedures into SOPs identify the hazards that may be encountered and specify practices and procedures designed to minimize or eliminate exposure to these hazards. SOPs, in fact, can and should dictate the ventilation strategy of a new lab or optimize the efficiency of the ventilation system in an existing lab.

> Indoor air quality improvement in the working space has long been one of the most important subjects of the ventilation system designs.

As most conventional laboratories are equipped with mixing ventilation systems, the airborne chemicals would be vented out through the ceiling exhausts. The ventilation system should be operated at a flow rate that can reduce the chemical concentration in the occupied zone to a reasonably low level.

Higher ventilation flow rates in general result in lower average contaminant concentration. In a well mixed condition, the average chemical concentration will be linearly reduced when the ventilation flow rate increases. In typical labs, however, this does not hold to be true

---

Farhad Memarzadeh is affiliated with Division of Technical Resources, National Institutes of Health, 13 South Drive, MSC 5759, Bldg 13, Rm. 201, Bethesda, MD 20892-5759, United States (Tel.: 301 435 8746;
fax: 301 435 8686;
e-mail: FM30C@NIH.GOV).

As most conventional laboratories are equipped with mixing ventilation systems, the airborne chemicals would be vented out through the ceiling exhausts.

since the concentration can be quite non-uniform as a result of room airflow patterns, laboratory conditions, contaminant quantities and properties. Using standard ACH recommendations can lead to a false sense of safety and increased energy consumption because some locations may have higher than predicted contaminant concentrations and exposure may depend on where a person is located within the lab following contaminant emission. Taking into consideration that the amount of chemical removed per unit mass of ventilation air can become smaller at higher ventilation flow rate, and that there is an increased cost associated with higher ventilation flow rate, this study examines the need for and the cost relationship of contaminant removal for high ventilation flow to improve air quality in the presence of a bench exhaust system compared to a conventional ceiling exhaust system without bench slot exhausts.

While the bench exhaust system was proved, in a previous study,[4,17] to be able to capture the heat generated on the bench top, and therefore improve the thermal comfort and reduce the annual cooling cost, it is also necessary to access its performance in removing airborne chemicals caused by spill at the bench top. The purpose of this study is therefore to quantitatively compare the removal ability of a typical laboratory ventilation system with and without bench top exhausts at different flow rates when there is an accidental airborne chemical spill at the bench top.

METHODOLOGY

Airflow and heat transfer in rooms are governed by the fundamental conservation law in the form of the Navier-Stokes Equations:

$$\frac{\partial}{\partial t}(\rho\varphi) + \mathrm{div}(\rho\vec{V}\varphi - \Gamma_\varphi\,\mathrm{grad}\,\varphi) = S_\varphi$$

$$\text{Transient} + \text{Convection} - \text{Diffusion} = \text{Source} \qquad (1)$$

where **r** is the density; ∇ the velocity vector; W the dependent variable; G_w the exchange coefficient (laminar + turbulent); S_w is the source or sink term.

This set of equations is highly nonlinear, second-order partial differential equations for which there is no analytical solution available. Numerical procedure is currently the only way to solve the equations. Among the numerical procedures, Computational Fluid Dynamics (CFD) is the most widely used and very efficient methodology to investigate temperature and flow field in rooms where there are many parameters involved.[5–7] In addition, the output of the CFD simulation can be presented in many ways with the useful details of field distributions, as well as overviews on the effects of different parameters. Therefore, CFD is employed in this study,[8] and the turbulence is simulated with the k–e model.[9,10] The k–e turbulence model represents the most appropriate choice of model because of its extensive use in other research applications, such as predicting mixing rate of a jet flow and modeling airflow in urban open space.[11,12]

Two approaches can be used to simulate chemical spill dispersion in a space: (1) the particle trajectory tracking approach, and (2) the concentration approach. The particle trajectory approach is generally applied when the chemical cannot be treated as gaseous. Zhang et al.[13] used this approach to study biological contaminant control strategies in a hospital operating room. This approach involves two phase flow modeling, i.e., the continuous phase (air) is determined by CFD, and the particles are treated within the Lagrangian framework as trajectories. The concentration approach has been used to study the convection and dispersion of gaseous contaminants. Kassomenos et al.[14] used this approach to evaluate indoor air quality in a polyvinyl chloride chemical plant by estimating occupational exposure and to design its ventilation system. Li et al.[15] predicted the flow field and resulting worker exposures when toxic airborne contaminants were released into the wake region of a mannequin. The concentration approach solved the fraction of the contaminant in each control volume using the conservation equation of fraction coupled with the temperature and velocity fields. This approach can provide the contaminant distribution throughout the entire calculation domain. In this study, the concentration

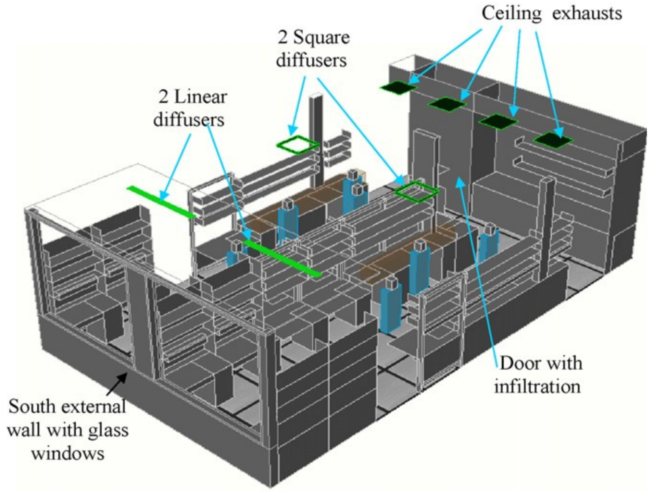


Figure 1. Laboratory layout.

Table 1. 10 Cases with Variation in the Ventilation System and Flow Rate.

Case Description	Total Supply Flow Rate CFM	Door Gap Infiltration CFM	Number of Ceiling Exh.	Total Ceiling Exh. Flow Rate CFM	Bench Exh. Flow Rate CFM
14 ACH	1670	200	4	−1870	0
14 ACH with bench exh.	1670	200	4	−1070	−800 (−200/bench)
12 ACH	1430	200	4	−1630	0
12 ACH with bench exh.	1430	200	4	−830	−800 (−200/bench)
10 ACH	1210	200	2	−1410	0
10 ACH with bench exh.	1210	200	2	−610	−800 (−200/bench)
8 ACH	970	200	2	−1170	0
8 ACH with bench exh.	970	200	1	−370	−800 (−200/bench)
6 ACH	730	200	2	−930	0
6 ACH with bench exh.	730	200	1	−130	−800 (−200/bench)

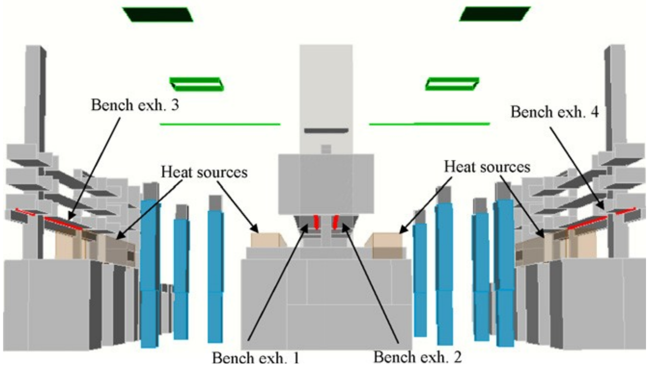


Figure 2. Locations of bench exhausts and bench heat sources.

approach was used since chemical evaporated from a spill at the bench is gaseous.

MODEL SET UP

A generic laboratory with a conventional air distribution system, shown in Figure 1, was used in this study. The same laboratory space was modeled with different ventilation schemes in 10 cases as listed in Table 1. There was no fume hood in this lab. The total heat generation from the bench devices, shown in Figure 2, was 5808 W. The lighting heat sources were 2275 W. There were 7 occupants in the room. The sensible heat from each occupant was assumed to be 80 W. Solar loading from south-facing windows on the external wall was divided as 1160 W transmitted into the room and 1273 W absorbed by the glass and the external wall section. The supply temperature was 11.1 8C (52 8F) for all cases. The bench exhausts used in this study were continuous slots along the length of the benches, mounted beneath shelves of the bench as shown in Figure 2. Two occupied zones, the walking zone and the bench zone, were defined to compare the performance of different ventilation schemes. The walking zone covers the areas of aisles and the doorways from the floor to 1.8 m (71 in.) above, and the bench zone includes all benches from the top of the bench to 1.8 m high (71 in.), as highlighted in Figure 3.

This study considers, in a steady state condition, the ventilation system performance at different flow rates, with and without bench slot exhausts, in removing gaseous chemical from the room if there is an accidental chemical spill on the bench top. The chemical spill was modeled as a source located at the center of the affected bench, either at Location 1 or at Location 2, as highlighted in Figure 4. The chemical concentration was assumed to be 1×10^6 ppm at the top of the chemical source. The gaseous chemical from the source was dispersed in the room by convection and diffusion and the dis-

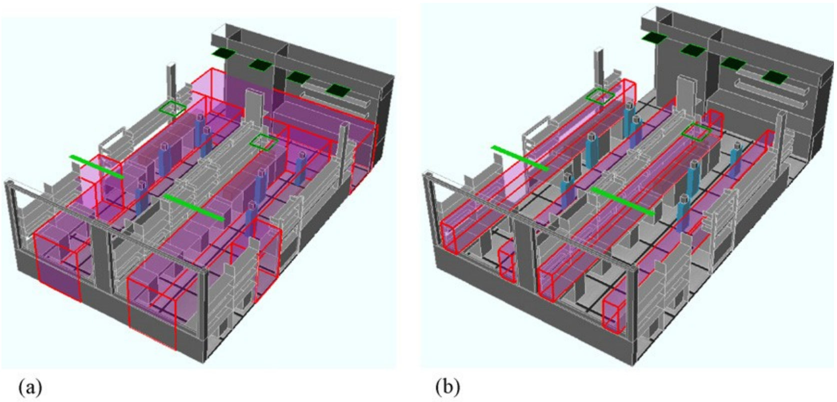


Figure 3. Two occupied zones. (a) Walking zone: defined as the volume of 1.8 m from the floor in the 5 highlighted areas. (b) Bench zone defined as the volume above the bench top to 1.8 m in the 4 highlighted areas.

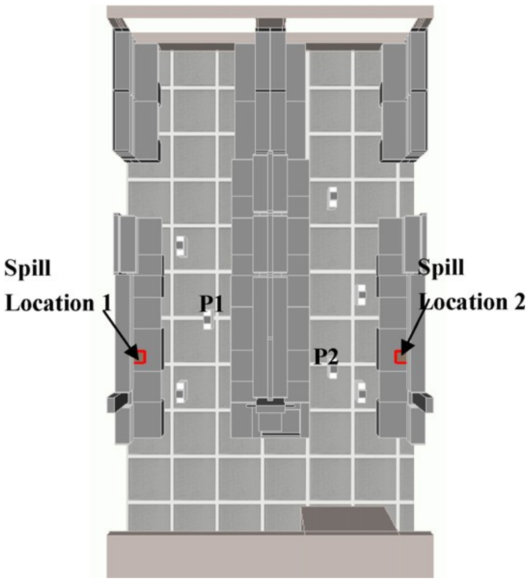


Figure 4. Locations of spill and the 2 positions being monitored.

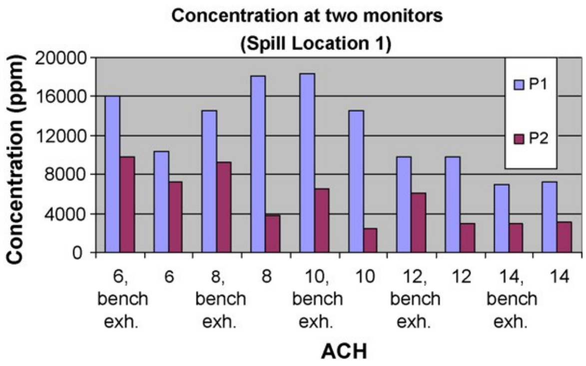


Figure 5. Concentration at breathing level of the 2 occupants with Spill location 1.

tribution of the chemical concentration was computed in the CFD simulations. The removal effectiveness of the ventilation system at different flow rates is evaluated and compared.

RESULTS AND DISCUSSION

Three parameters are used to assess the performance of the ventilation system at different flow rates in chemical removal: the concentration at selected occupants' breathing level, the average concentration in the occupied zone and contaminant removed by per unit mass flow rate of the ventilation air.

The concentrations at the breathing level in front of two occupants, as marked in Figure 4, are plotted in Figures 5 and 6 concerning the two assumed spill source locations. The figures show that the concentration at the breathing level of the occupant close to the spill was much higher than that of the one who was in an aisle away. Comparing 6 ACH and 10 ACH at Position 1 in Figure 5 and at Position 2 in Figure 6 reveals that the concentration was not necessarily lower when the ventilation flow rate increased. When using bench top exhausts in the presence of ceiling ventilation, a lower ACH did not appear to have a significant affect on contaminant removal at these two locations.

To compare the efficiency of the ventilation air in removing the bench top spills, Figure 7 presented the amount of chemicals being removed per unit mass flow rate of the ventilation air. The efficiency of the ventilation air as measured by chemical removal noticeably decreased when the flow rate increased. For example, at 6 ACH (without bench top exhaust) average kilogram of ventilation air removed 0.023 kg of chemical, while at 12 ACH, it only removed 0.014 kg of chemical.

In a perfect mixing condition, the chemical concentration in the room at steady state follows a linear decay when ventilation flow increases. In a transient process of chemical removal, the time required for a given removal efficiency (90%, 99%, and 99.9%) also linearly decreases with increase of ventilation flow rate.[16] However, this does not apply to all cases since perfect mixing is not typically achieved. The average concentration level in the occupied zones with the two spill locations is plotted in Figures 8 and 9. The average concentration in the occupied zone was generally reduced when the ventilation

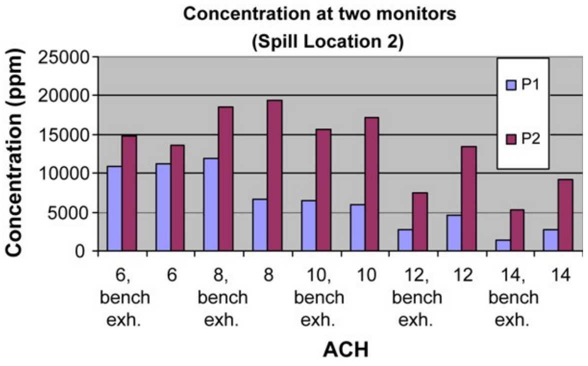


Figure 6. Concentration at breathing level of the 2 occupants with Spill location 2.

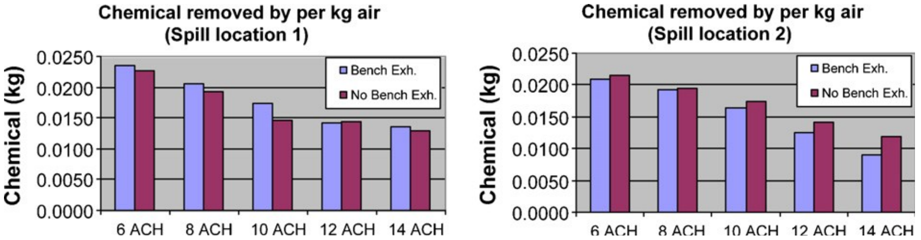


Figure 7. Amount of chemical removed per kg of ventilation air.

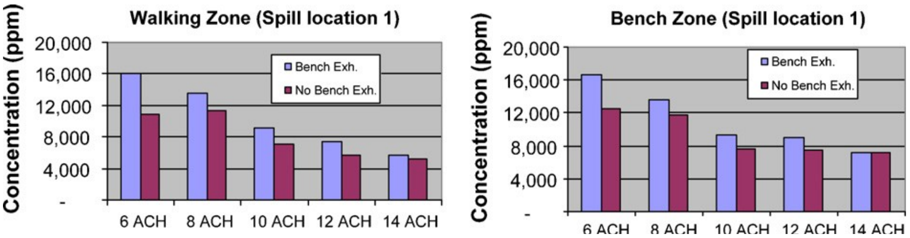


Figure 8. Average concentrations in the occupied zones with Spill location 1.

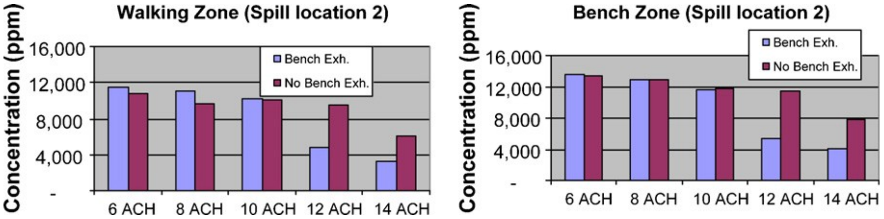


Figure 9. Average concentrations in the occupied zones with Spill location 2.

flow rate increases. However, it was by no means linearly decayed with the ventilation flow rate increase, especially for the cases without the bench top exhausts. For example, with Spill location 2, the change of average concentration in the occupied area was unremarkable when the ventilation flow rate was doubled from 6 ACH to 12 ACH as presented in Figure 9.

Our previous study[1] shows that the bench exhaust system at 480 CFM flow had a negligible effect on the hood containment. It also demonstrates that the fume hood greatly reduced the concentration level due to bench top spills since gaseous chemical was less likely to re-circulate and be trapped in the room. It is true that the hood containment is not perfect, and there is always a very small fraction of contaminant mass that would leak from the hood to the room depending on the hood extract flow rate, the placement of the contaminant source inside the hood, the sash opening size, the turbulence level around the sash opening, etc. However, the contaminant concentration due to the hood leaking decays quickly from the sash opening. Our previous study addressed a scenario in which a bench exhaust system has great potential to improve air quality by effectively removing airborne chemicals caused by a spill at the bench top. In this study, however, using bench top exhausts does not seem to be as beneficial in removing the chemical spill at bench top. This can be caused by the instability of the flow and the difference in thermal boundary condition assumptions of the two studies, which results in change in local flow pattern. It can also be due to the way the heat generation and the chemical spill were modeled in the two studies. As the bench exhausts were continuous long slots, they well covered the heat sources which were sized for the bench top. The chemical spill on the bench top was modeled as small rectangular surface, therefore, the useful section of

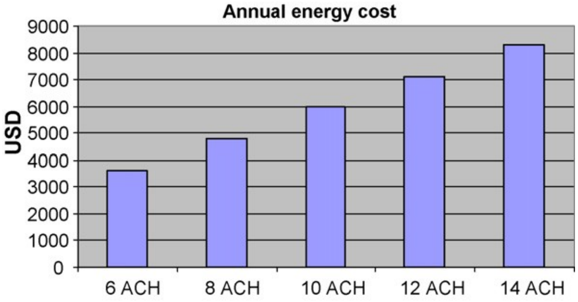


Figure 10. Annual HVAC energy cost for a typical laboratory located in Washington DC.

the bench top exhaust was only a small section close to the spill. In addition, the bench top exhausts could increase the local velocity around the source, resulting in a higher contaminant generation rate.

Figure 10 compares the annual energy costs of different ventilation flow rates for a typical 70 m^2 lab located in Washington DC area. When reducing ventilation flow rate from 12 ACH to 6 ACH, which does not seem to have significant impact on the chemical concentration in the occupied zones in case a bench top spill occurs, a 49% saving in annual energy cost can be achieved.

The main assumptions used in this calculation are listed below;

- The outdoor temperatures are taken from weather data in Washington DC.
- The percentage of outdoor air is 100% for both cases.
- Supply air temperature is 11.1 °C (52 °F) for cooling and 31 °C (88 °F) for heating. The Relative Humidity of supply air is assumed to be 50%.
- Cooling load per CFM is calculated as the difference in air enthalpy when entering and leaving the HVAC system. Perfect duct insulation is assumed.
- Heating load per CFM is based on Dry Bulb Temperature difference of air entering to and leaving from HVAC system. Perfect duct insulation is assumed.
- Humidification load is based on the difference in Humidity Ratio between leaving and entering air.
- Steam load for process applications is estimated to be 10,000 PPH. Plant steam required for generating humidification steam (untreated steam) is 1.33 times the humidification load.
- The cost of electricity is 0.1$/KWH, fuel is $8.0/MMBtu; chilled water generation efficiency is 1.0 KW/TON; fan efficiency is 68%.

CONCLUSIONS

Considering the fact that the chemical operated on the bench top is generally safe, the thermal comfort requirement is, therefore, the main concern of a typical lab. Our previous study[4] suggested that, with bench exhausts, the ventilation flow rate could be as low as 6 to 8 ACH to meet the thermal comfort requirement in a typical lab. This system also had a negligible effect on the containment ability of a fume hood located upstream from the bench. This study shows that the reduced ventilation flow rate is also adequate for air quality concern in case a bench top spill occurs without the bench exhaust system. With carefully designed ceiling exhaust locations in the room, the concentration in the space should be sufficiently low to cause any health concern. When reducing ventilation flow rate from 12 ACH to 6 ACH, a 49% saving in annual energy cost for a typical lab in the Washington DC area can be achieved without having a significant impact on the chemical concentration in the occupied zones in the case of a bench top spill.

Considering the fact that the chemical operated on the bench top is generally safe, the thermal comfort requirement is, therefore, the main concern of a typical lab.

A bench exhaust system may be beneficial in certain circumstances as it has been shown to be effective in controlling the removal of local contaminants. However, it may not be cost effective in a situation where the use of non-toxic chemical spills are infrequent and the use of well designed SOPs are employed to handle these chemicals.[17,18] Accidents do happen and when they occur, the conventional ventilation design using ceiling exhausts and a fume hood, with 6 ACH proves to be an effective strategy to decrease contaminant concentration and reduce energy costs. Further investigations may be required on the effectiveness of using bench top exhausts in removing bench top chemical spill. The evidence in this CFD study leans heavily towards using considerably lower ACH in a laboratory setting, specifically reducing the typical 12 ACH to much lower ACH. Using a conventional ventilation system without bench exhausts at 6 ACH provides a cost savings in both design and energy consumption, while also providing adequate contaminant control and thermal comfort for the occupants. Although the evidence demonstrates that the bench exhaust system improves thermal comfort and provides an energy savings, further study is needed to determine and optimize when the cost of a bench exhaust system justifies its use as a contaminant control strategy.

REFERENCES

1. Memarzadeh, F.; Manning, A.; Jiang, Z. Energy efficient laboratory design—A new approach to improve indoor air quality and thermal comfort. 24th International Conference on Passive and Low Energy Architecture Transactions, Vol. 1 (pp. 799–810). 2007, p. 799–810.
2. Memarzadeh, F. Methodology for Optimization of Laboratory Hood Containment, Report Volume 1 of 2; Division of Engineering Services, National Institute of Health, 1996.
3. Huang, H.; Haghighat, F. An integrated IAQ model for prediction of VOC emissions and sinks by building material. Proceedings of the 4th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Vol. 1 (pp. 381–388). 2001, p. 381–388.
4. Memarzadeh, F. Controlling Laboratory IAQ and Energy Costs, Heating, Piping, and Air-Conditioning Engineering (HPAC), October, 2007.
5. Jiang, Z.; Chen, Q.; Haghighat, F. Airflow and air quality in large enclosures. ASME J. Solar Energy Eng. 1995, 117, 114–122.
6. Memarzadeh, F. Ventilation Design Handbook on Animal Research Facilities Using Static Microisolators; National Institutes of Health, Office of the Director; Bethesda, 1998.
7. Haghighat, F.; Jiang, Z.; Zhang, Y. Impact of ventilation rate and partition layout on VOC emission rate: time-

dependent contaminants removal. Int. J. Indoor Air Qual. Climate, 1994, 4, 276–283.

8. FLOVENT, Reference Manual 1995, Flomerics, FLOVENT/RFM/0994/1/1.
9. Wilcox, D. C. Turbulence Modeling for CFD; DCW Industries Inc.; La Canada, California, 1993.
10. Chen, Q. Comparison of different k–e models for indoor airflow computations. Numerical Heat Transfer, Part B: Fundam. 1995, 28, 353–369.
11. Gregory-Smith, D. G.; Smith, A. G.; Cutbill, S. C.; Tumelty, M. Modelling coanda effect flows using PHOENICS. PHOENICS J. 1996, 9(2), 229–252.
12. Palmer, G.; Vazquez, B.; Knapp, G.; Wright, N.; Happold, B. The apratical application of CFD to wind engineering problems. Proceedings of the Eighth International Conference (pp. 995–999). 2003, p. 995–999.
13. Zhang, R.; Tu, G.; Ling, J. Study on biological contaminant control strategies under different ventilation models in hospital operating room. Build. Environ. 2008, 43(5), 793–803.
14. Kassomenos, P.; Karayannis, A.; Panagopoulos, I.; Karakitsios, S.; Petrakis, M. Modelling the dispersion of a toxic substance at a workplace. Environ. Model. Softw. 2008, 23(1), 82–89.
15. Li, J.; Yavuz, I.; Celik, I.; Guffey, S. Predicting worker exposure—the effect of ventilation velocity, free-stream turbulence and thermal condition. J. Occup. Environ. Hyg. 2007, 4(11), 864–874.
16. Morbidity and Mortality Weekly Report Recommendations and Reports ‘‘Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Settings’’, Vol. 54/No. RR-17, 20, 2005.
17. Memarzadeh, F. Ventilation Strategy for Laboratories, Cover Story; Heating, Piping, and Air-Conditioning Engineering (HPAC), August, 2007.
18. Memarzadeh, F.; Manning, A.; Jiang, Z. Energy efficient laboratory design: A novel approach to improve indoor air quality and thermal comfort. Am. Biol. Saf. Assoc. (ABSA) J. 2007, 12(3).