ENERGY EFFICIENT AIR QUALITY CONTROL IN LABORATORIES USING BENCH EXHAUSTS

Farhad Memarzadeh[1†], Jane Jiang[2], and Andy Manning[2]

[1] *PhD, PE, National Institutes of Health, Bethesda, MD, USA*
[2] *PhD, Flomerics, Inc. Marlboro, MA, USA*

ABSTRACT

The air quality in laboratories has a profound affect on occupant health and safety. Reducing the time of exposure and the amount of contaminant can improve the occupant environment and have direct impact on health and safety. In this study, a novel ventilation system which introduces bench exhausts is proposed. The system offers the potential for application in new and existing research laboratories to effectively remove airborne contaminants at the bench using a technology that is cost effective and efficient. This study is focused on the indoor air quality aspect of the ventilation scheme in laboratories. The effectiveness of the bench exhausts in removing contaminants at the bench top is investigated for cases with and without a fume hood present in the test space. The bench exhausts, fume hood and the ceiling mounted ventilation system are compared qualitatively in their ability to remove contaminants The fume hood containment is also evaluated with different ventilation arrangements. The results indicate that bench exhaust technology has great potential to improve air quality by effectively removing airborne contaminants at the bench top if a fume hood is not in the laboratory area. However, when a fume hood is   in the same space, the benefits of bench exhausts are reduced.

KEYWORDS

Air Quality, CFD, Numerical Analysis, Bench Exhausts, Laboratory

INTRODUCTION

The ventilation systems used in buildings can be, in general, classified into three types. In the first type, air is supplied to the room from the ceiling and exhausts at the floor, or, alternatively, supplied from one wall and exhausted at the opposite wall, in a parallel manner. The air diffusers usually cover the entire ceiling or wall. This type of ventilation system creates a vertical or horizontal unidirectional flow in the room with a piston-like effect, and the supply velocity is usually low. Unidirectional flow systems are typically used in clean rooms. The second type is the displacement ventilation system. In this system, the air is supplied at lower-than-room temperature with a low velocity diffuser placed at floor level, and is exhausted at ceiling level. As the supply air temperature is lower than the temperature in the occupied zone, it fills the lower part of the room, resulting in vertical temperature stratification with a higher temperature in the upper part of the room. This system can be used in residential and commercial buildings, and for industrial assembly areas. The third type of ventilation system, the mixing ventilation system, was used in this study. It is widely used in laboratories with high cooling load in which diffusers are usually installed on a wall near the ceiling or on the ceiling. The supply velocity is usually much higher than the acceptable level in the occupied zone with a temperature above, below or equal to the air temperature in the occupied zone depending on the heating or cooling load. The region between the ceiling and the occupied zone serves as an entrainment region for the supply jet where there is an expected decay of the main jet velocity, and the temperature difference between the supply air and the room air becomes smaller due to the increment in the mass flow rate of the jet. In the case when the buoyancy and radiation effect is significant, for example, a room having a high cooling load in the occupied zone, this air diffusion system generates a counteraction of natural convection. The purpose of this system is to create an extract air condition in the room, while the displacement ventilation is to create a supply air condition in the room. The mixing ventilation system is widely used in laboratories.

[†] Corresponding Author: *E-mail address: memarzaf@ors.od.nih.gov*

Laboratories are usually equipment intensive. Often the equipment is sized for the bench top and powered from raceways. Many chemicals used in laboratories are harmful to the occupants' health. Inhalation exposure is a common concern raised by laboratory occupants. Indoor air quality improvement in the working space has long been one of the most important subjects of the ventilation system designs [1-3]. If there is a chemical spill on the bench top, it will evaporate and be dispersed in the room by convection and diffusion mechanisms. In particular, there is a need to control the migration of airborne contaminants and maximize the laboratory hood containment when applicable. It is well known that the room geometry, ventilation system, diffuser placement and operational procedure within a laboratory all play a role in contaminants removal effectiveness. As most laboratories are equipped with mixing ventilation systems, the airborne contaminants will likely be vented out through the ceiling exhausts. The contaminants moving towards the exhaust vent will be mixed with room air and spreads into the occupied zone of the laboratory. If exhaust outlets are located at the bench top where the contamination would be most likely to occur from experimental processes, it is hypothesized that a large portion of the contaminants can be captured at the source. The resulting air quality in the room can be improved. Considering the dual need to control the heat load produced by the equipment and the air quality, the ventilation requirements for laboratories provide a unique demand on HVAC design.

PURPOSE OF THIS STUDY

This study suggests that a bench top ventilation strategy can provide improved air quality as well as an overall cost reduction in the cooling plants, supply and exhaust air equipment and distribution ductwork.

The purpose of this study is to:

- Investigate the contaminants removal effectiveness of the bench exhausts for cases with and without a fume hood in the adjacent space.
- Compare the performance of the bench exhausts, fume hood and the ceiling mounted ventilation system in removing airborne contaminants.
- Evaluate fume hood containment with different ventilation arrangements.
- Demonstrate overall cost reduction and energy efficiency

METHODOLOGY

Computational Fluid Dynamics (CFD) is a very powerful and efficient methodology to investigate temperature and flow fielding in a room where there are many parameters involved [4-6]. 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 [7] to solve the fundamental conservation equations that govern the airflow and heat transfer in the form of the Navier-Stokes Equations:

$$\frac{\partial}{\partial t}(\rho\varphi) + div\,(\rho\,\vec{V}\,\varphi - \Gamma_{\varphi}\,\mathrm{grad}\;\varphi) = S_{\varphi} \qquad (1)$$

Transient + Convection - Diffusion = Source

Where :

ρ = density
$\vec{V}$ = velocity vector
φ = dependent variable
Γ_{φ} = exchange coefficient (laminar + turbulent)
S_{φ} = source or sink term

This set of equations can be solved numerically by superimposing a 3D-grid system of many hundreds of thousands of cells over a calculation domain which describes the physical geometry heat/contamination sources and air itself. Figure 1 shows a typical research laboratory and the corresponding space discretization, subdividing the laboratory into the cells.

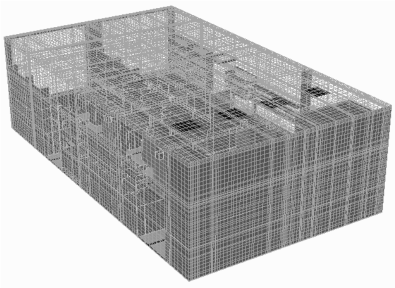


Figure 1 Super imposed grid of cells for calculation

In this study, a finite-volume approach was used to consider the discretization and solution of the equations. The simultaneous equations thus formed are solved iteratively for each one of these cells, to produce a solution that satisfies the conservation laws for mass momentum and energy. As the airflow in a ventilated laboratory is turbulent, the turbulence is simulated with the k-ε model [8-9] in this study. The k-ε 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 [10-11].

MODEL SET UP

A generic laboratory that had one island bench and wall benches, equipped with a conventional air distribution system was developed as the baseline laboratory model as shown in Figure 2.

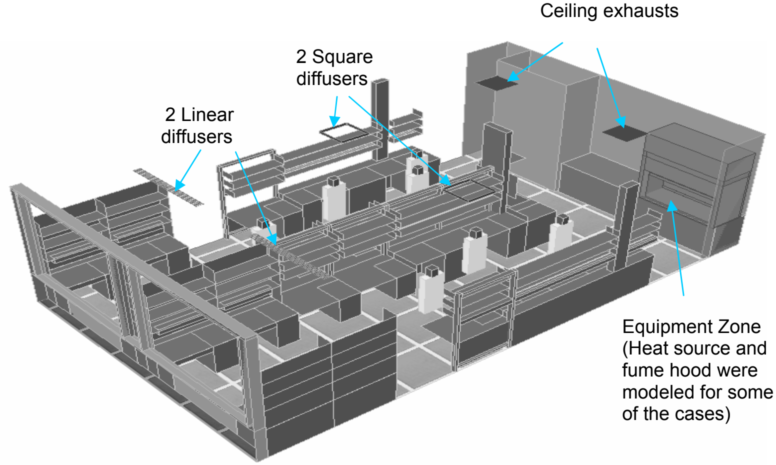
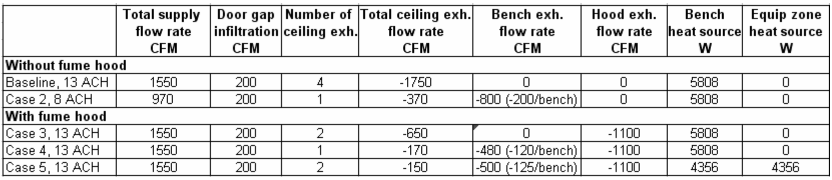


Figure 2 Laboratory layout for the baseline model

The same laboratory space was then modeled with the bench exhaust ventilation scheme and fume hood in 4 other cases listed in Table 1.



	Total supply flow rate CFM	Door gap infiltration CFM	Number of ceiling exh.	Total ceiling exh. flow rate CFM	Bench exh. flow rate CFM	Hood exh. flow rate CFM	Bench heat source W	Equip zone heat source W
Without fume hood								
Baseline, 13 ACH	1550	200	4	-1750	0	0	5808	0
Case 2, 8 ACH	970	200	1	-370	-800 (-200/bench)	0	5808	0
With fume hood								
Case 3, 13 ACH	1550	200	2	-650	0	-1100	5808	0
Case 4, 13 ACH	1550	200	1	-170	-480 (-120/bench)	-1100	5808	0
Case 5, 13 ACH	1550	200	2	-150	-500 (-125/bench)	-1100	4356	4356

Table 1. 5 cases with variation in the ventilation system and heat source

The results were compared to the baseline model. The following assumptions were made in the model laboratory for this study.

- Room dimension: 6.35m wide, 11m long and 3.2m high.
- Ventilation system: Two square diffusers and two linear diffusers on the ceiling with ceiling exhausts as shown in Figure 2. Flow rate varies from case to case. 200 CFM inflow through the door gaps due to infiltration.
- Supply temperature: 11.1°C (52°F) for all cases.
- Heat sources: The total heat generation from the bench devices was either 5808W or 4356W. The heat generated from the equipment zone was also considered in Case5 as shown in Table 1. The total lighting heat sources from the ceiling and the workbench were 2083W and 192W, respectively.
- Occupants: 7 occupants each generating 80W sensible heat.
- Environment: The external ambient was assumed to be 31.5°C (88.7°F) with external convective heat transfer coefficient of 6W/m-K. Solar loading from south-facing windows on the external wall was divided as 1160W transmitted into the room and 1243W absorbed by the glass. Another 30W was through the external wall section. The ceiling, floor and walls were assumed to be adiabatic. Surface to surface radiation was not modeled in this study.

The bench exhausts used in this study were continuous local exhaust air slots along the length of the lab benches, all 2” wide, mounted beneath shelves of the bench as shown in Figure 3.

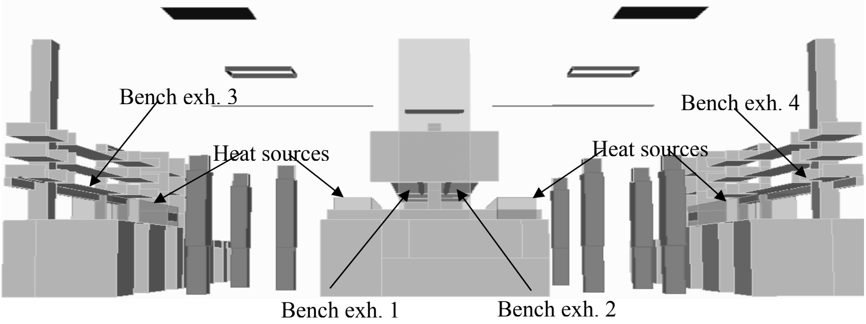


Figure 3 Locations of bench exhausts and bench heat sources

The fume hood modeled in Cases 3 through 5 extracted 1100 CFM from the room. The sash of the hood was assumed to be at its maximum open position, 0.64M. The hood was placed at the corner of the equipment zone as indicated in Figure 2. In the Cases 4 and 5 both fume hood and bench exhausts were installed. There was not fume hood in Baseline and Case 2.

In order to examine how the bench exhausts function in removing contaminants from the room, a chemical spill on the bench top at two different locations was considered. 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.

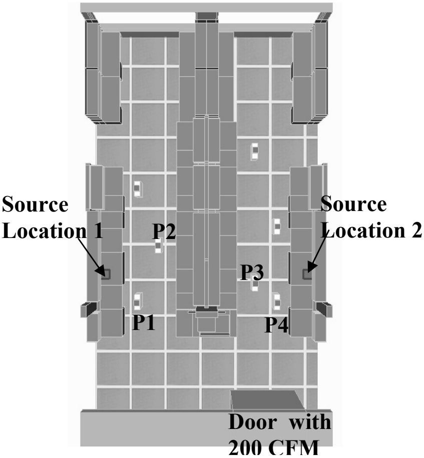


Figure 4 Locations of contaminants

The concentration was assumed to be 1x10^6 ppm at the top of the contaminants source. With the existence of the source, the contaminants was dispersed in the room by convection and diffusion, and the distribution of the contaminants concentration was computed in the CFD simulations.

Two sets of occupied zone were defined for evaluating and comparing the performance of different ventilation schemes: the walking zone and the bench zone. The walking zone covers the areas of aisles and the doorways from the floor to 1.8m above, and the bench zone includes all benches from the top of the bench to 1.8m high, as highlighted in Figures 5 and 6, respectively.

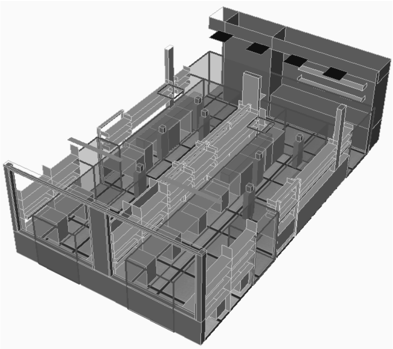


Figure 5 Walking zone: defined as the volume of 1.8m from the floor in the 5 highlighted areas

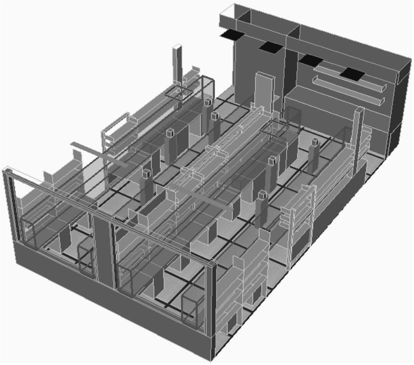


Figure 6 Bench zone defined as the volume above the bench top to 1.8m in the 4 highlighted areas

RESULTS

The effectiveness of exhausts in contaminants removal can be evaluated with the following parameters: the concentration at the occupants' breathing level; the average concentration in the occupied zone; and the percentage of the contaminants removed by these exhausts. The effect of bench exhausts on hood containment is also addressed. The concentration at the breathing level in front of the four occupants positioned closer to the source, as marked in Figure 4, are monitored for Baseline and Case 2, and are plotted in Figures 7 and 8 for the two assumed source locations. It is observed that concentration level is generally lower in Case 2 than that in Baseline model even with a 30% less overall ventilation flow rate. The positions closest to the contaminants sources, Position 1 to Location 1 and Position 4 to Location 2, benefit the most by the bench exhausts. Without bench exhausts, these positions were in direct downstream of the sources where the contaminant concentrations were usually highest.

The average concentration level in the occupied zones with the two source locations are plotted in Figure 9 for the 5 cases. The fume hood in Cases 3-5 greatly reduces the concentration level in the occupied zone. This is because the change of flow pattern that results in less contaminant being recirculated and trapped in the occupied zone, which is a convincing example that shows how the exhaust location can affect the air quality in the rooms. The results of baseline case and Case 2 shown in Figures 7 through 9 indicate that by using bench exhausts, the contaminants concentration in occupied space can be even lower when ventilation flow rate of the lab is reduced from 13 ACH to 8 ACH. This leads to a 37% saving in annual HVAC operation cost for a typical lab in the Washington DC area as shown in Figure 10.

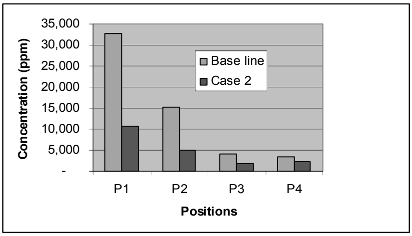


Figure 7 Concentration at breathing level of the 4 occupants with source Location 1

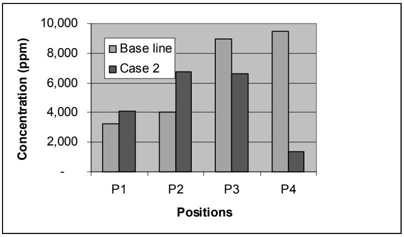


Figure 8 Concentration at breathing level of the 4 occupants with source Location 2

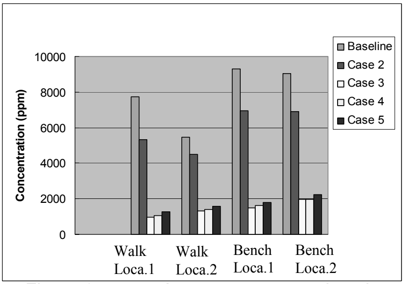


Figure 9 Average concentrations in the walking and bench zones with two locations of contaminant source.

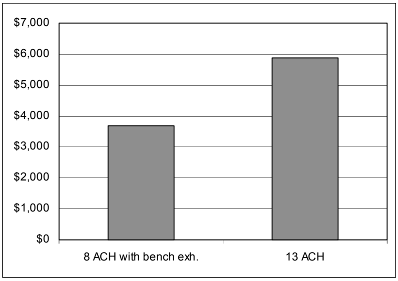


Figure 10 Annual HVAC operation cost for a typical laboratory located in Washington DC

Table 2 shows the percentages of contaminants removed by the exhausts with the two source locations. The data show that a significant amount of the contaminants is removed by fume hood even when the source is quite far from the hood (Location 2). This is mainly due to the higher exhaust flow rate at the hood than at ceiling and bench exhausts. For source Location 2, the hood extracts about 15% - 27% less contaminant than when the source is located in Location 1. The data also indicate that the bench exhausts are not as beneficial in removing the contaminants when the fume hood is used. This may be explained as the interaction between the flow being extracted to the bench exhausts and the main flow stream towards the fume hood. Figure 11 compares the removal effectiveness of the ceiling and bench exhausts by presenting the ratio of contaminant removed by per CFM air at the bench exhaust above the source to that removed by per CFM air at the ceiling exhaust.

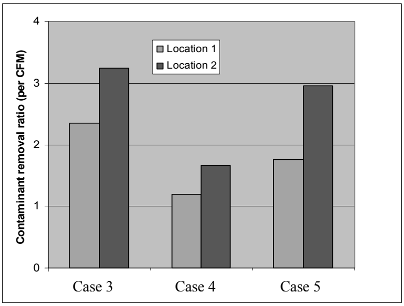


Figure 11 The ratio of contaminant removed by per CFM airflow at the bench exhaust above the source over that at the ceiling exhaust for two source locations.

In this plot, the benefit of using the bench exhaust for bench top contaminant removal is obvious. Because bench exhausts were located close to the contaminant sources, a large portion of the contaminant could be captured at the source. Especially for Case 2 in which the bench exhaust above the source removes contaminants 2.3 to 3.2 times higher than that removed by ceiling exhausts. The ratios are consistently higher for source Location 2. This may be due to the 200 CFM infiltration from the door gap that is closer to Location 2 as shown in Figure 2. This 200 CFM uncontaminated flow would take up the extracting airflow volume at the ceiling exhausts, resulting in lower concentration level.

As the room geometry, ventilation system, diffuser/exhaust locations and operational procedure within a laboratory all affect the airflow, it is necessary to assess how the bench exhausts would influence the containment of the hood. In an ideal case, the contaminants generated from a source at the sash opening would be nearly 100% removed by the hood. In reality, however, the contaminants will leak backward into the room by turbulent diffusion even if there is no recirculation at the sash opening. The lower the contaminant leakage, the better is the hood containment and, therefore, the contaminants concentration in the room. In order to calculate the containment of the hood, the sash opening was filled with contaminant released towards the inside of the hood to represent a worst case scenario. The contaminants mass leaking back into the room was represented through an imaginary box that was placed in front of the sash opening extending 12” outside the sash opening as shown in Figure 12.

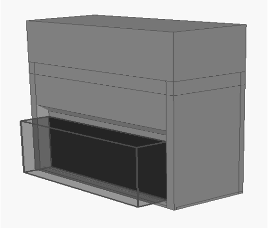


Figure 12 Sash opening and the imaginary box in front of the sash opening.

The total contaminants leaking into the room was the summation of the net leakage at the 5 faces of the imaginary box. The leakage factor, defined as the fraction of contaminant mass flow rate leaking from the hood to the room against the contaminant mass removed by the hood exhausts, can be used to evaluate the hood containment. This definition has the same meaning as the Box leakage factor introduced in Reference [1].

The leakage factor results are shown in Figure 13.

Figure 13 The fraction of contaminant mass flow rate leaking from the hood to the room against the contaminant mass removed by the hood exhausts for Cases 3-5

Cases 3 and 4 are very similar in terms of heat source distribution and overall ventilation flow rate. The main difference between the two cases is that Case 4 has bench exhausts taking 480 CFM from the room. The fact that the leakage factors for these two cases, 0.00182 and 0.00183, are very close to each other leads to the conclusion that the bench exhausts with a total 480 CFM flow have a negligible effect on the hood containment. In Case 5, the leakage factor at 0.00212 is noticeably higher than that in Case 4 although the overall ventilation flow rates are the same and the bench exhaust flow rates of the two cases are very close. The flow entering the sash opening is generally a one-directional flow because of the strong extraction of the hood exhausts. Therefore leakage from the hood is mainly a result of turbulent diffusion around the sash opening. In Case 5, there is a heat source of 4356W in the equipment zone next to the hood as described in Figure 2. The buoyancy effect caused by the equipment heat source enhances the turbulence level around the sash opening area, resulting in higher leakage factor of this case.

CONCLUSIONS

(1) Bench exhausts demonstrate great potential in improving air quality by effectively removing contaminants on benches. The results indicate that the average contaminants concentration in the occupied zones and the local concentration at the breathing points of occupants monitored are all decreased in the presence of bench exhaust. The positions close to the contaminants sources are even more benefited by the bench exhausts.

(2) The fume hood does have a noticeable effect on the ability to improve air quality. When a fume hood is used, the benefits of bench exhausts are not as remarkable.

(3). The bench exhausts in the cases studied have negligible effect on the hood containment.

(4) The saving in annual HVAC operation cost for a typical laboratory located in Washington DC is around 37% when the proposed bench exhausts are used.

(5) Further investigation is required to define the optimal ventilation conditions required to maintain a satisfactory thermal comfort level and a contaminants capture rate consistent with the results of this study.

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