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Determining IAQ Dynamic Response to Emissions

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ABSTRACT

To achieve acceptable indoor air quality (IAQ), ASHRAE Standard 62-1989 recommends the use of the alternative IAQ procedure.. The IAQ procedure can treat both constant-volume and variable-air-volume (VAV) with constant or proportional outside airflow rates. The relationships in Appendix E of the standard must be used in conjunction with the IAQ procedure to directly calculate indoor air contaminant concentrations in an occupied space. However, these relationships may not provide sufficient information to fully analyze system operation at part-load conditions, and particularly, to predict dynamic variations of contaminant concentrations during the day. Determination of indoor air contaminant concentrations vs. time of the day can be used as a design strategy to provide IAQ compliance in new construction and remodeling as well as a means to monitor whether maximum allowable concentrations are reached in old buildings.

This paper will first demonstrate the development of a dynamic model for each of the seven heating, ventilating and air-conditioning (HVAC) systems listed in the standard, and will apply this dynamic modeling to estimate the concentrations of formaldehyde and particulates (PM_{10}) as a function of time in an office occupancy for three types of filters.

1.0 INTRODUCTION

Emissions from indoor contamination sources such as building materials, consumer products, etc. are the primary determinant of IAQ. In achieving acceptable IAQ, ASHRAE Standard 62-1989 prescribes the use of the alternative IAQ procedure. This procedure can be used to treat both constant-volume and VAV with constant or proportional outside airflow rates.

Appendix E (Table E-1) of the standard also provides relationships to be used in conjunction with the IAQ procedure to directly calculate indoor air contaminant concentrations in an occupied space, and also to verify the adequacy of the outside ventilation airflow rates obtained by the Ventilation Rate (VR) procedure. However, these relationships may not provide sufficient information to fully analyze system operation at part-load conditions, and especially, to predict dynamic variations of indoor air contaminant concentrations throughout the day[1]. Determining dynamic variations can serve as a design strategy to provide IAQ compliance in new construction and remodeling as well as monitoring purposes. It provides a means to control indoor air contaminant concentrations cost-effectively than using excessive outside air (dilution).

In this paper, we will first develop a dynamic model for each of the seven most commonly used HVAC systems listed in ASHRAE Standard 62-1989, and then demonstrate how this dynamic modeling works by providing an example. In this example, we will estimate the concentrations of formaldehyde as a function of time in an office occupancy for three types of ASHRAE-rated filters, and outline how one can choose filters to decrease outside airflow requirement. Formaldehyde is the most dominant indoor air contaminant in newly constructed and remodeled buildings. Urea-formaldehyde-foam insulation (UFFI), particle boards, some paper products, fertilizers, chemicals, glass and packaging materials are the major sources of formaldehyde. In addition, we will estimate the indoor air contaminant concentrations of PM_{10} as a function of time for the same office occupancy for monitoring purposes.

2.0 DEVELOPING A DYNAMIC MODEL

Figure 1 shows a new model obtained by modifying the model in Appendix E of ASHRAE Standard 62-1989 to include diffusion. Applying a mass-balance for this model gives:

$$m_s = m_g + m_{v,in} - m_{r,out} - m_f - (m_{ia} - m_{ra}) \quad (1)$$

where

m_g: mass of contaminant generated in space,
$m_{v,in}$: mass of contaminant supplied with outside air,
$m_{r,out}$: mass of contaminant exhausted with return air,
m_f: mass of contaminant captured by filter,
m_{ia}: mass of contaminant absorbed by surfaces in space, and
m_{ra}: mass of contaminant re-absorbed.

In this model, it is assumed that densities of return air and outside air are the same, contaminant is generated continuously at a steady-rate, and no infiltration or leakage occurs. The filter is either located in the recirculated air (location A) or in the mixed air (location B). Eqn. (1) is further simplified by denoting the net effect of absorption (m_{ia} - m_{ra}) as m_a, where $m_{ia} > m_{ra}$. The ventilation effectiveness (E_v) is assumed to be 1.0 (perfect mixing). The concentration of a contaminant at any interval of time, *dt* in a space can be calculated by writing a differential equation for filter location A:

$$QdC_s(t) = Ndt + C_oV_odt - C_s(t)V_odt - C_s(t)(V_s - V_o)E_fdt - C_s(t)V_adt \quad (2)$$

and for filter location B:

$$QdC_s(t) = Ndt + (1-E_f)C_oV_odt - C_s(t)V_odt - C_s(t)(V_s - V_o)E_fdt - C_s(t)V_adt \quad (3)$$

where

$C_s(t)$: concentration of contaminant at time *dt*,
Q: volume of space,
N: contaminant emission rate,
C_o: concentration of contaminant in outside air,
V_o: flow rate of ventilation air,

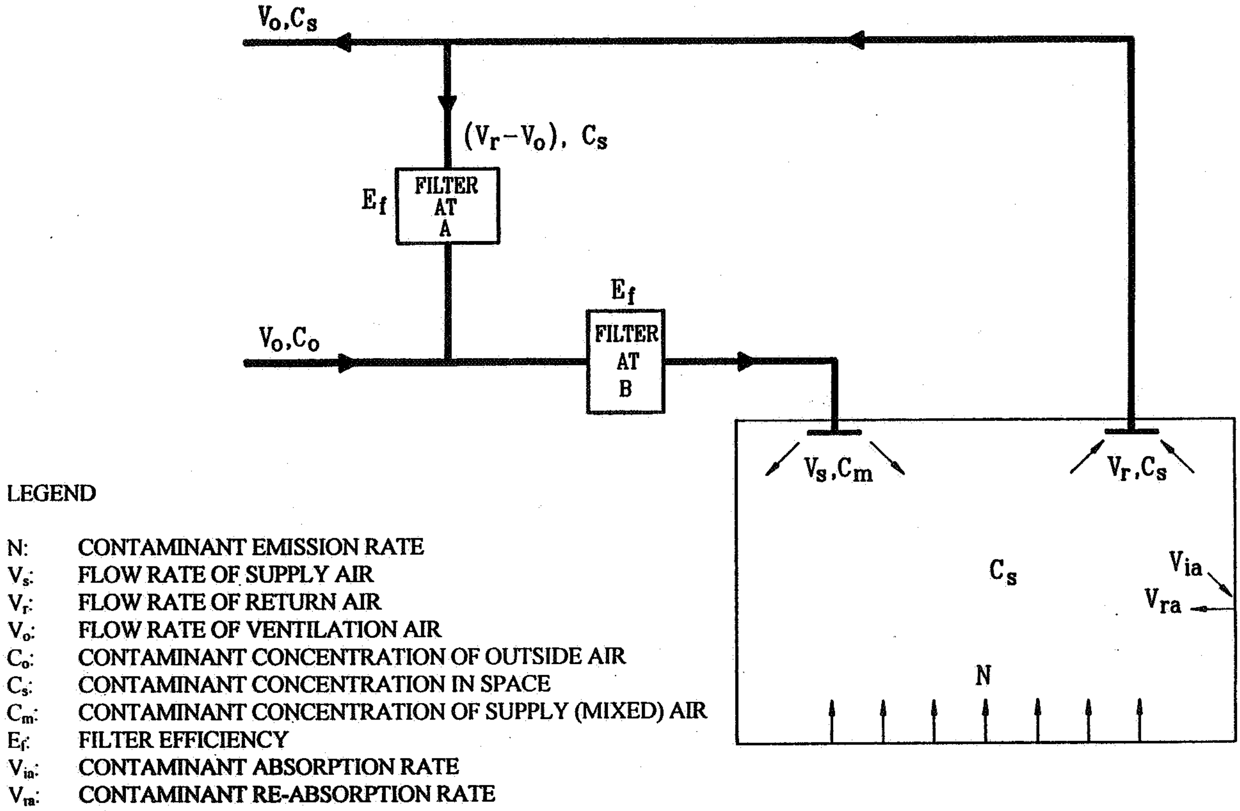


Figure 1. A Model to Determine Concentrations of Contaminants for Filter Locations A and B.

V_s: flow rate of supply air,
E_f: filter efficiency, and
V_a: flow rate of absorbed air.

Solving Eqn. (2) and Eqn. (3) above provides the general solutions in Eqn. (4) and Eqn. (5) for filter locations A and B, respectively.

$$C_s(t) = C_s(t-1)\exp\{-[V_o + V_a + E_f(V_s - V_o)]\, t/Q\} + [(C_oV_o + N) / (V_o + V_a + E_f(V_s - V_o))]\,\{1 - \exp\{-[V_o + V_a + E_f(V_s - V_o)]\, t/Q\}\} \qquad (4)$$

$$C_s(t) = C_s(t-1)\exp\{-[V_o + V_a + E_f(V_s - V_o)]\, t/Q\} + \{[(1-E_f)\, C_oV_o + N] / (V_o + V_a + E_f(V_s - V_o))\}\{1 - \exp\{-[V_o + V_a + E_f(V_s - V_o)]\, t/Q\}\} \qquad (5)$$

where

$C_s(t-1)$: initial concentration of contaminant in space.

Depending on the filter location, either Eqn.(4) or Eqn.(5) is then solved for $C_s(t)$ for each class of HVAC systems in Table E-1 of the standard, therefore, creating a distinct model for each class. The resulting dynamic equations are presented in Table 1 for Classes I through VII. Furthermore,

Table 1. Contaminant Concentration as a Function of Time for HVAC System Classes I through VII.

HVAC System Class	Filter Location	Flow	Temperature	Outside Air	Space Contaminant Concentration
I	None	VAV	Constant	100%	$C_s(t) = C_s(t-1) + [C_s(t-1) - C_o]\exp(-V_o t/Q) + \frac{N}{V_o}[1 - \exp(-V_o t/Q)]$
II	A	Constant	Variable	Constant	$C_s(t) = C_s(t-1)e^{-x} + \frac{C_o V_o + N}{V_0 + E_f(V_s - V_o)}(1 - e^{-x})$
III	A	VAV	Constant	Constant	$C_s(t) = C_s(t-1)e^{-y} + \frac{C_o V_o + N}{V_0 + E_f(F_r V_s - V_o)}(1 - e^{-y})$
IV	A	VAV	Constant	Proportional	$C_s(t) = C_s(t-1)e^{-z} + \frac{C_o F_r V_o + N}{F_r V_0 + F_r E_f(V_s - V_o)}(1 - e^{-z})$
V	B	Constant	Variable	Constant	$C_s(t) = C_s(t-1)e^{-x} + \frac{(1-E_f)C_o V_o + N}{V_0 + E_f(V_s - V_o)}(1 - e^{-x})$
VI	B	VAV	Constant	Constant	$C_s(t) = C_s(t-1)e^{-y} + \frac{(1-E_f)C_o V_o + N}{V_0 + E_f(F_r V_s - V_o)}(1 - e^{-y})$
VII	B	VAV	Constant	Proportional	$C_s(t) = C_s(t-1)e^{-z} + \frac{(1-E_f)F_r C_o V_o + N}{F_r V_0 + E_f F_r(V_s - V_o)}(1 - e^{-z})$

Note: Exponents x, y and z above are computed as follows:

$$x = \frac{t}{Q}[V_o + E_f(V_s - V_o)] \qquad y = \frac{t}{Q}[V_o + E_f(F_r V_s - V_o)] \qquad z = \frac{tF_r}{Q}[V_o + E_f(V_s - V_o)]$$

the net effect of absorption and re-absorption (or "sink" effects) in Eqn. (4) and Eqn. (5) is omitted because data gathered to date indicate that the sink effects are negligible.

2.1 Evaluating IAQ in New Construction and Remodeling

We will now demonstrate how dynamic modeling can be used in estimating the concentration of formaldehyde in new construction or remodeling. In this example, formaldehyde is assumed to be emitted from resilient flooring, painted surfaces and furniture. The contaminant emission rate of formaldehyde is estimated to be approximately 4.44 $\mu g/m^3$-min per Table H-1 of the draft ASHRAE Standard 62-19XX.

Consider an office occupancy of 93 m^2 with a Class VI HVAC system. A maximum occupancy of 7 people per 93 m^2 is assumed in accordance with ASHRAE Standard 62-1989. Referring to Table 1, the Class VI HVAC system has a VAV system with a filter at location B, and constant temperature and constant outside ventilation airflow rate.

The Class VI HVAC system may have various filter types with different efficiencies. Figure 2 shows the contaminant removal efficiencies of several ASHRAE-rated filters on a mass-mean-diameter (MMD) basis of particulates in microns. For example, the contaminant removal efficiency of an ASHRAE-rated (40%) filter at an MMD of 2.0 microns, is 15%. In our calculations, we will use Type 1 (40%, ASHRAE-rated), Type 2 (60%, ASHRAE-rated) and Type 3 (90%, ASHRAE-rated) filters with corresponding contaminant removal efficiencies of 15%, 50% and 95%.

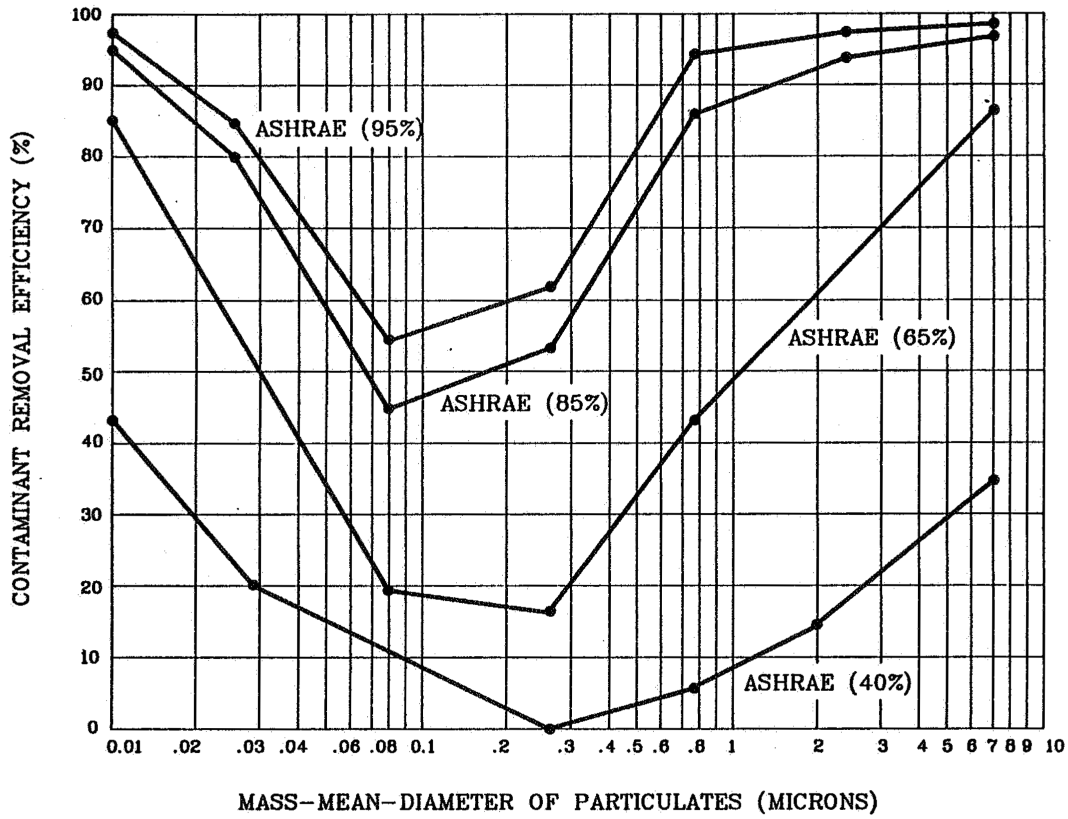
Table C-1 of the draft ASHRAE Standard 62-19XX provides target concentration guidelines for most common indoor air contaminants. For this example, the target (maximum allowable) concentration of formaldehyde is approximately 0.1 parts per million (ppm) (or 122 $\mu g/m^3$). Based on this allowable concentration, the calculated outside airflow requirement for the office occupancy is 154 L/s (or 22 L/s/person) for new construction and 84 L/s (or 12 L/s/person) for remodeling, if dilution is the only method used to decrease formaldehyde concentrations to allowable levels. These rather high and, therefore costly outside air requirements (in comparison to 9.5 L/s/person for an office occupancy per ASHRAE Standard 62-1989) may be significantly decreased by the use of air-cleaning in combination with proper filtration. Air-cleaning refers to removal of particulates in both gaseous and vapor phases.

To demonstrate a sample calculation, the following variables are used:

$E_f = 0.15$ (15%)
$C_o = 0.0\ \mu g/m^3$
$V_s = 708$ L/s
$V_o = 154$ L/s
$Q = 255\ m^3$
$N = 4.44\ \mu g/m^3$-min (at full occupancy)
$F_r =$ flow reduction factor

The C_s of formaldehyde as a function of time can be calculated by solving the following equation in Class VI of Table 1.

$$C_s(t) = C_s(t-1)\exp(-y) + \{[(1-E_f)\, C_oV_o + N] / [V_o + E_f\,(F_rV_s - V_o)]\}\ [1 - \exp(-y)]$$



Source : EPA Research Triangle

Figure 2. Contaminant Removal Efficiency of Several ASHRAE-Rated Filters.

where

$$y = [t/Q]\ [V_o + E_f\ (F_r V_s - V_o)]. \tag{6}$$

Figure 3 shows how the C_s of formaldehyde various hourly depending on the Type 1, Type 2 and Type 3 filter efficiencies during the day with variable occupancy. For comparison purposes, Figure 3 also shows the projected performance with dilution air but without an air-cleaning system. As can be seen from Figure 3, filters with higher contaminant removal efficiencies result in considerably decreased indoor air contaminant concentrations in new construction or remodeling.

Dynamic modeling can be used as a design strategy to deal with high concentrations of formaldehyde in new and remodeled buildings. Not only does this strategy verify the compliance of contaminant concentrations obtained by dilution, it also determines the time of day at which maximum concentrations occur. In Figure 3, maximum formaldehyde concentrations occur between 7:00 am and 9:00 am, and 5:00 pm and 6:00 pm for all three types of filters.

To avoid these maximum concentrations while decreasing the outside air requirement to around 9.5 L/s/person, one needs to use a higher efficiency filter. In this case, holding everything constant, same calculations need to be performed with V_0 = 9.5 L/s/person to observe how these curves behave, and choose the curve with a filter efficiency that will eliminate or minimize the period of time in which maximum concentrations occur. The dynamic modeling described here provides a method to ensure compliance with allowable contaminant concentrations at all times;

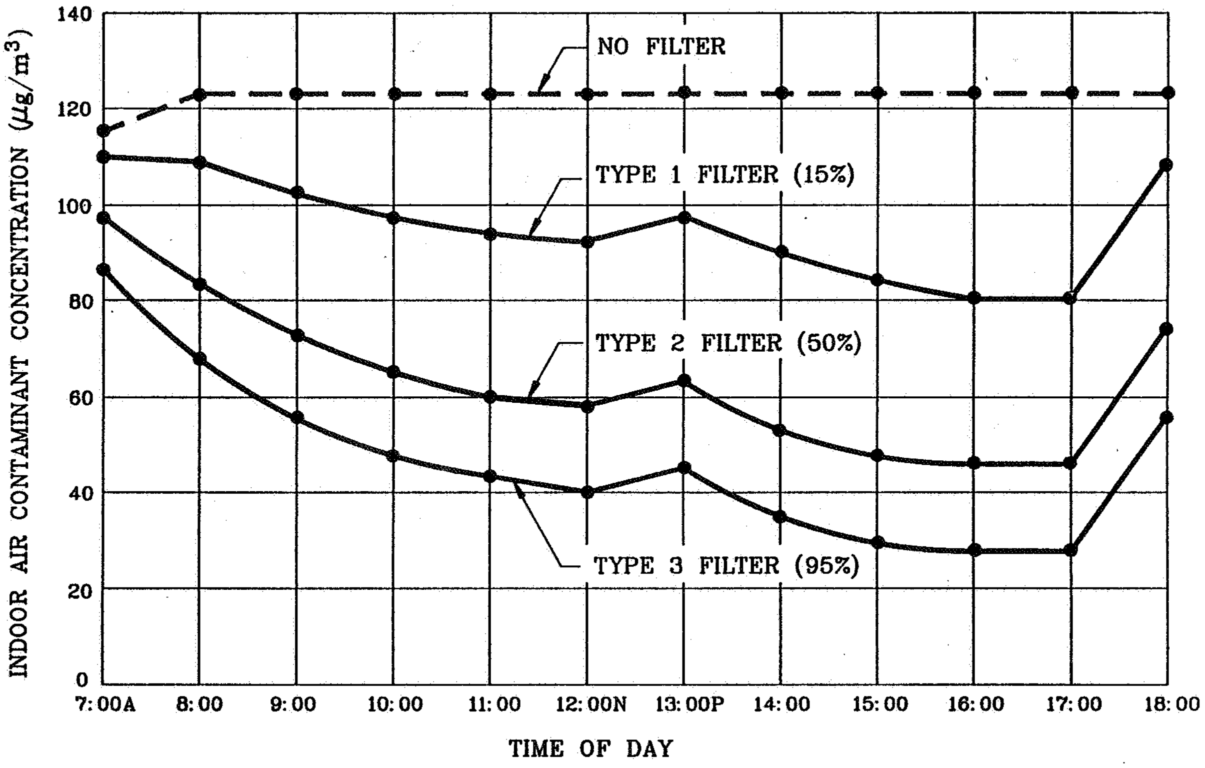


Figure 3. Concentration of Formaldehyde in an Office Occupancy with a Class VI HVAC System and Type 1, Type 2 and Type 3 Filters.

emphasizes the very important role air-cleaning and filtration play in attaining allowable contaminant concentrations and, therefore, acceptable and cost-effective IAQ; and provides a useful means to evaluate HVAC system operation, especially for VAV systems at part-load conditions.

2.2 Monitoring Indoor Air Contaminant Concentrations by Dynamic Modeling

Considering the same office occupancy with a Class VI HVAC system as before, let us now estimate $C_s(t)$ of PM_{10} for Type 1 (40%, ASHRAE-rated), Type 2 (60%, ASHRAE-rated) and Type 3 (90%, ASHRAE-rated) filters with corresponding contaminant removal efficiencies of 18%, 56% and 95%. Again, contaminant removal efficiencies of ASHRAE-rated filters in this example are based on an MMD of particulates in microns. The emission rate of PM_{10} is estimated to be approximately 0.018 $\mu g/m^3$-min per Table H-1 of the draft ASHRAE Standard 62-19XX. Per Table C-1 of the draft ASHRAE Standard 62-19XX, the maximum allowable C_s of PM_{10} is approximately 50 $\mu g/m^3$.

The C_s of PM_{10} as a function of time can be calculated by again solving Eqn.(6). Figure 4 shows how the C_s of PM_{10} varies hourly depending on the Type 1, Type 2 and Type 3 filter efficiencies during the day with variable occupancy. For comparison purposes, Figure 4 also shows the projected performance with dilution air but without an air-cleaning system. In this example again (refer to Figure 4), filters with higher contaminant removal efficiencies result in considerably decreased C_s of PM_{10}.

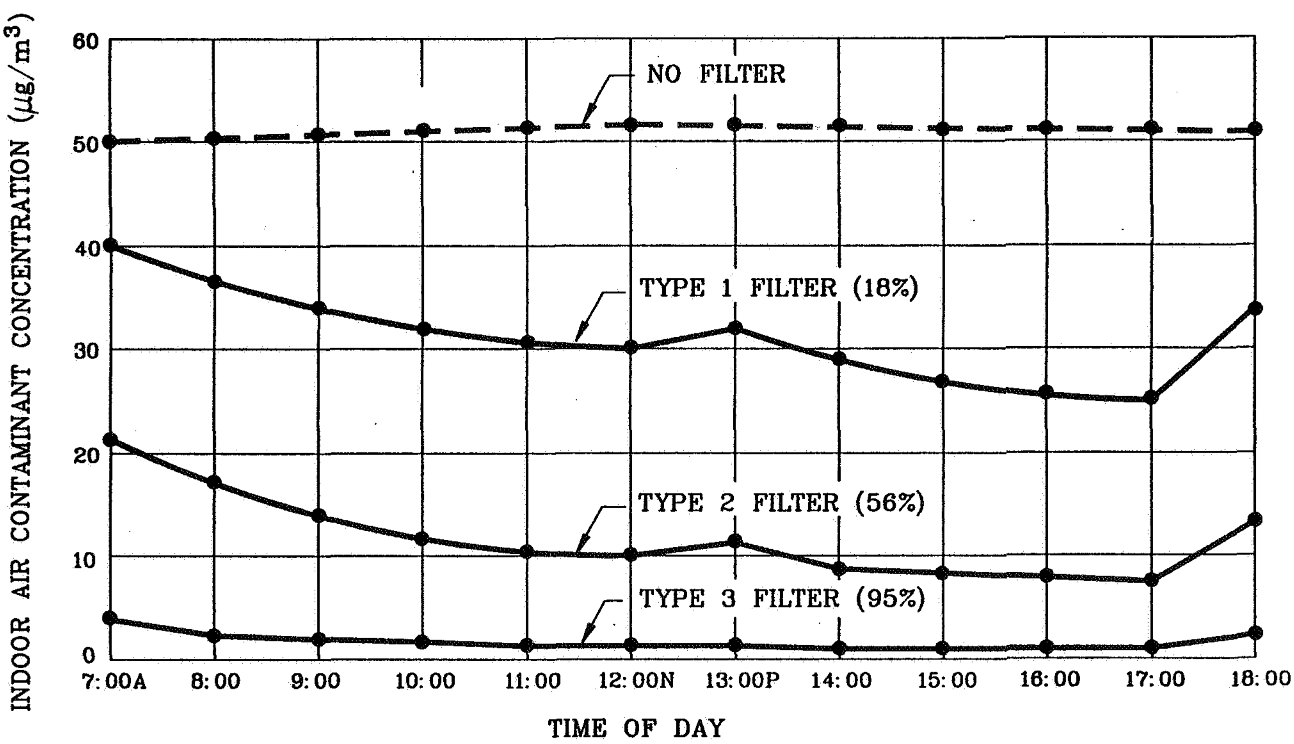


Figure 4. Concentration of PM_{10} in an Office Occupancy with Class VI HVAC System and Type 1, Type 2 and Type 3 Filters.

As can be seen from Figure 4, the monitored maximum PM_{10} concentrations occur between 7:00 am and 9:00 am, and 5:00 pm and 6:00 pm for all three types of filters and they are in compliance with allowable levels. Should these concentrations become significant or exceed the allowable levels, they may be eliminated or minimized simply by choosing a higher efficiency filter. Choosing an appropriate high-efficiency filter can help outside ventilation airflow rate decrease, resulting in significant energy saving while providing acceptable IAQ.

3.0 REFERENCE

[1]MECKLER, M.
"Dynamic Response Models for IAQ Performance Evaluation"
ASHRAE Winter Meeting, Seminar 01, 1995.