THE IMPACT OF FILTER PLACEMENT IN AIR-CONDITIONING SYSTEMS ON THE BEHAVIOR OF INDOOR CONTAMINANT CONCENTRATION

Ismail M. Budaiwi[1]

1: Associate professor, Architectural Engineering Department, KFUPM, Dhahran, Saudi Arabia

E-mail: ibudaiwi@kfupm.edu.sa

ABSTRACT

Air filters in air-conditioning systems play a major role in sustaining a healthy indoor environment. The effectiveness of the filter in achieving acceptable indoor air quality depends on its contaminant removal efficiency and the way it is placed within the air-conditioning system. The objective of this paper is to study the impact of filter placement on transient and steady state contaminant concentration. A theoretical single-zone indoor air quality model is utilized. Results indicate that filter placement within the HVAC system relative to the source of contaminant and circulating air streams can have an appreciable impact on indoor contaminant concentration behavior. In order to enhance the overall effectiveness of the air filtration system, it is recommended that HVAC designers evaluate the impact of filter placement on indoor contaminant concentration as part of the filtration system design procedure. General guidelines for filter placement are given as part of the conclusions of this research.

Keywords: *filter placement, HVAC system, IAQ, indoor contaminant concentration*

الـملخص

تلعب منقيات الهواء في أجهزة التكييف والتهوية دورا مهما في الحفاظ على بيئة صحية داخل المباني ، وتعتمد فعالية نظام تنقية الهواء في الحصول على جودة مقبولة للهواء الداخلي على مدى قدرته على التخلص من العوالق الملوثة للهواء ، وكذلك على الطريقة التي تم وضعه بها في نظام التكييف والتهوية . تهدف هذه الورقة إلى دراسة تأثير وضع منقيات الهواء بالنسبة لحركة الهواء في نظام التكييف و التهوية على مستوى تركيز الملوثات وتغييرها مع الوقت . وقد أوضحت النتائج أن وضع منقيات الهواء ومكانها في نظام التكييف والتهوية له تأثير كبير على سلوك تركيز الملوثات. لذلك فيجب على مصممي أنظمة التكييف والتهوية الإلمام بمدى هذا التأثير ومعرفة العلاقة بين فعالية منقيات الهواء ووضعها في نظام التكييف والتهوية ومصدر الملوثات ليتسنى لهم زيادة فعالية نظام تنقية الهواء. يخلص البحث بإعطاء بعض الإرشادات العامة التي تفيد في تحديد الموضع الأمثل لمنقيات الهواء في نظام التكييف والتهوية.

1. INTRODUCTION

Maintaining an acceptable air quality in buildings requires the removal of particulate and gaseous contaminants from both the ventilation and the re-circulated air. In buildings, media filters and electronic air cleaners are commonly used devices for cleaning air from particulate contaminants such as: dust, fibers, lint and plant pollen. Electronic air cleaners are highly efficient in removing the smallest particles. The effectiveness of media filters, on the other hand, varies according to filter type, the physical characteristics of the contaminant (i.e., particle size) and, to some extent, on the velocity of the air stream [McQuiston and Parker, 1988]. Additionally, filter performance depends to a great extent on the way it is installed. For good performance, filters should be accessible for inspection and maintenance and should cover the whole airflow path, allowing no air to bypass the filter media [Wilkinson, 2001].

Depending on the required degree of air cleanliness and the nature of the contaminant, the filter system type is selected and the maintenance procedure is specified. The filter is then sized to accommodate the required airflow rate and flow resistance. More than one filter can be placed at different locations along air streams in the air-conditioning system. For example, air filters can be placed to separately filter the make-up air and the return air before being mixed, or a single filter can be placed after the mixing point. Filter placement is a crucial design issue that affects the indoor air quality and contaminant concentration behavior. However, the relationship between filter location and actual contaminant behavior is not well understood by HVAC designers. The placement of filters is normally selected so that the air is filtered before entering the air-conditioning equipment rather than afterward [McQuiston and Parker, 1988]. Additional criteria for location selection include the source of the contaminant and the practical considerations related to accessibility, safety and ease of maintenance [ASHRAE, 1996].

The impact of filtration on indoor contaminant concentration and the importance of proper filtration system design and methodologies for producing acceptable indoor air quality has been emphasized in the literature [Muller and England, 1995; Giles, 1987; Schafer and Kotz,, 1987; Burroughs et al, 1999; Owen et al, 1993]. However, scant attention is given to the effect of filter placement on the behavior of contaminant concentration within the space. Filter placement in the air-conditioning system can significantly affect the transient and the steady state concentration of the indoor contaminant and consequently the quality of indoor air. The objective of this paper is to theoretically investigate the impact of filter placement on contaminant concentration behavior. A single-zone enclosure indoor air quality model is used to evaluate the transient and steady state contaminant concentration with different filter placements. Results are expected to help HVAC designers better understand and appreciate the issue and its impact on IAQ and hence aid judgment when deciding where to place filters within the air-conditioning system.

Top

2. THE MODELING APPROACH

A single-zone transient indoor air quality model, which is based on the mass balance concept, is utilized to predict contaminant concentration behavior within an enclosure with different filter placements. In order to obtain a better understanding of the model's results, the sources of the contaminant are limited to the supply air and the indoor generation process, with the return air as the only active sink as shown in *Figure 1*. The model assumes that perfect mixing occurs in the space, and that filter efficiency variations with airflow rate and time (i.e., due contaminant accumulation on filter material) are negligible.

By employing the mass balance concept, the following equation is obtained:

$$VdC_i / dt = \sum m\dot{c} = Q_s C_s - (Q_r + Q_e)C_i + \dot{N} \tag{1}$$

Solving the above equation requires the knowledge of contaminant concentration in the supply air C_s, which is dependent on the contaminant concentration of the indoor air as well as the performance of the filtration system. Substituting for the supply air contaminant concentration in terms of indoor and outdoor contaminant concentrations as well as the filtration system efficiency, the above equation can be arranged to yield:

$$dC_i / dt = \mathrm{A}C_i + \mathrm{B} \tag{2}$$

Expressions for contaminant concentration in the supply air required in Equation 1 and the parameters B and A in Equation 2 are given in *Table 1* for different filtration system schemes.

Solving Equation 2, the instantaneous contaminant concentration for all cases can be generally expressed by:

$$C_i(t) = (C_{io} + \mathrm{B}/\mathrm{A})\exp(\mathrm{A}t) - \mathrm{B}/\mathrm{A} \tag{3}$$

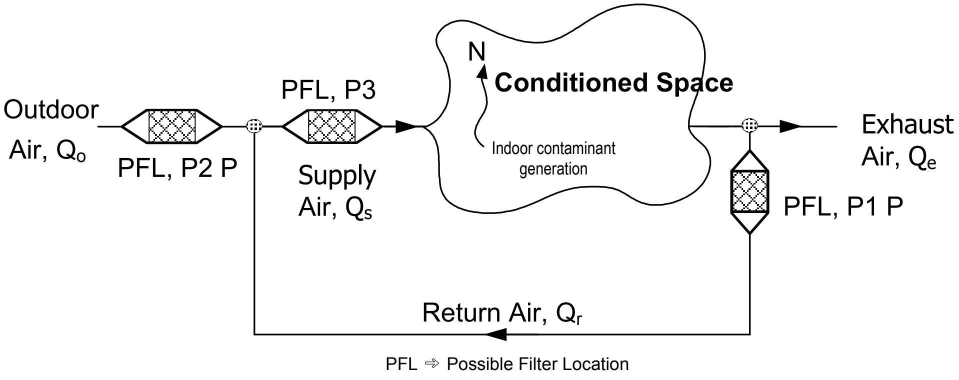

Figure 1 A schematic of possible filter locations in the HVAC system

Top

3. APPLICATION EXAMPLE

In order to investigate the impact of filter placement on contaminant concentration, the transient and steady state concentration of a contaminant in a single-zone enclosure is predicted utilizing the above model with the filter placement schemes given in *Table 1*. The number of filters and/or filter location is changed in each scheme. The enclosure volume is 150 m^3 and the supply air rate (Q_s) is 0.05 m^3 /s, which is assumed to be equal to the return air rate (Q_{rn}). The re-circulated air rate is taken as 80% of the supply air rate by volume (i.e., α_r), which means that an equivalent of 20% of the supply air volumetric flow rate is exhausted to the outdoors. The outdoor contaminant concentration is assumed at 50 mg/m^3, and the indoor contaminant generation rate is 0.5 mg/s. The efficiency of the filters in all locations is assumed constant at 70%.

4. RESULTS AND DISCUSSIONS

The concentration behavior of the indoor contaminant varies according to the way the contaminant is introduced to the space as well as the efficiency and effectiveness of the ventilation systems in removing it. In buildings most contaminants found in the indoor air are either brought in from the outside through the make-up air or generated indoors. In either case, contaminant concentration behavior is influenced by the ability of the filtration system to remove the contaminant from the re-circulated air and ventilation air. Needless to say, the ability of the filtration system to clean up air streams is dependent on the location of the filter in the air-conditioning system relative to the source of the contaminant. In order to illustrate this relationship, contaminant concentration behavior in the single zone enclosure described in the application example is evaluated for the seven cases of filter locations indicated in *Table 1*. For each case, the transient and steady state contaminant concentrations are predicted when the outdoor air is the source of contaminant and when the contaminant is generated indoors. *Table 2* illustrates the time constant (in seconds) and the steady state contaminant concentration for the seven cases and *Figures 2* and *3* show the transient response of the contaminant concentration when outdoor air contaminant concentration C_o is 50 mg/m^3 and the rate of indoor contaminant generation N, is 0.5 mg/s.

From Table *2*, it can be seen that the time constant is independent of the contaminant source, but significantly varies with filter placement and arrangement. The time constant is an important indicator of the transient behavior of contaminant concentration describing the speed at which the final status (i.e. steady state) of the contaminant is attained. The least time constants are obtained for case 5 and case 7. In both cases, two filters are placed along with the closed loop of air circulation, one is placed after the mixing point and the other is placed in the re-circulated air loop. It is evident that the outside air filter placed prior to the mixing point does not have any impact on the time constant, but considerably affects contaminant concentration behavior including steady state conditions. When the outdoor air is the source of contaminant as shown in *Figure 2*, placing an outdoor air filter reduces steady state

Top

contaminant concentration by more than 60%. Obviously, when the contaminant is generated indoors, the outdoor air filter plays no role in shaping contaminant concentration behavior as can be seen for cases 5 and 7 in Figure *3*.

Table *1* Parameters of concentration behavior equations for different filter arrangements

Case No.	Number of Filters	Filter Location	Parameters of Concentration Behavior Equation
1	1	P1	$C_s = (1-\eta_r)\alpha_r C_i + (1+\alpha_r)C_o$ $\mathrm{A} = [(1-\eta_r)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\alpha_r)C_o Q_s + N]/V$
2	1	P2	$C_s = (1-\eta_o)(1-\alpha_r)C_o$ $\mathrm{A} = [\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_o)(1-\alpha_r)C_o Q_s + N]/V$
3	1	P3	$C_s = (1-\eta_m)[(1-\alpha_r)C_o + \alpha_r C_i]$ $\mathrm{A} = [(1-\eta_m)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_m)(1-\alpha_r)C_o Q_s + N]/V$
4	2	P1, P2	$C_s = (1-\eta_r)\alpha_r C_i + (1-\eta_o)(1-\alpha_r)C_o$ $\mathrm{A} = [(1-\eta_r)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_o)(1-\alpha_r)C_o Q_s + N]/V$
5	2	P1, P3	$C_s = (1-\eta_o)(1-\eta_r)\alpha_r C_i + (1-\eta_o)(1-\alpha_r)C_o$ $\mathrm{A} = [(1-\eta_o)(1-\eta_r)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_o)(1-\alpha_r)C_o Q_s + N]/V$
6	2	P2, P3	$C_s = (1-\eta_m)\alpha_r C_i + (1-\eta_o)(1-\eta_m)(1-\alpha_r)C_o$ $\mathrm{A} = [(1-\eta_m)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_o)(1-\eta_m)(1-\alpha_r)C_o Q_s + N]/V$
7	3	P1, P2, P3	$C_s = (1-\eta_r)(1-\eta_m)\alpha_r C_i + (1-\eta_o)(1-\eta_m)(1-\alpha_r)C_o$ $\mathrm{A} = [(1-\eta_r)(1-\eta_m)\alpha_r Q_s - Q_{rn}]/V$ $\mathrm{B} = [(1-\eta_o)(1-\eta_m)(1-\alpha_r)C_o Q_s + N]/V$

Top

Table *2* Parameters of contaminant behavior equation for the application example

Case No.	**A**	**Time Constant (s)**	***Outdoor Air* is the Source of Contamination**		***Contaminant* is Generated Indoors**	
			B	**Steady State Concentration** mg/m^3	**B**	**Steady State Concentration** mg/m^3
1	-0.000253	3952	0.0030	13.04	0.0033	13.04
2	-0.000067	14925	0.0010	14.92	0.0033	49.30
3	-0.000253	3952	0.0010	3.95	0.0033	13.04
4	-0.000253	3952	0.0010	3.95	0.0033	13.04
5	-0.000310	3226	0.0010	3.20	0.0033	10.60
6	-0.000253	3952	0.0003	1.19	0.0033	13.04
7	-0.000310	3226	0.0003	0.97	0.0033	10.60

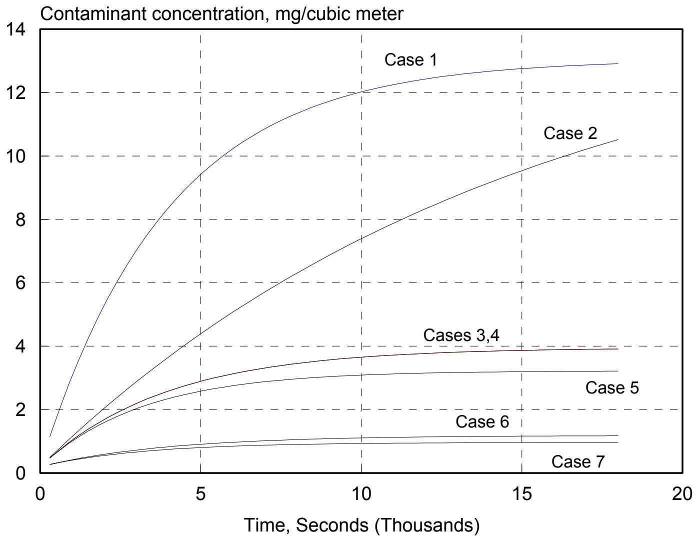

Figure *2* Concentration behavior of indoor contaminant at different filter arrangements when contaminant is generated indoors

Top

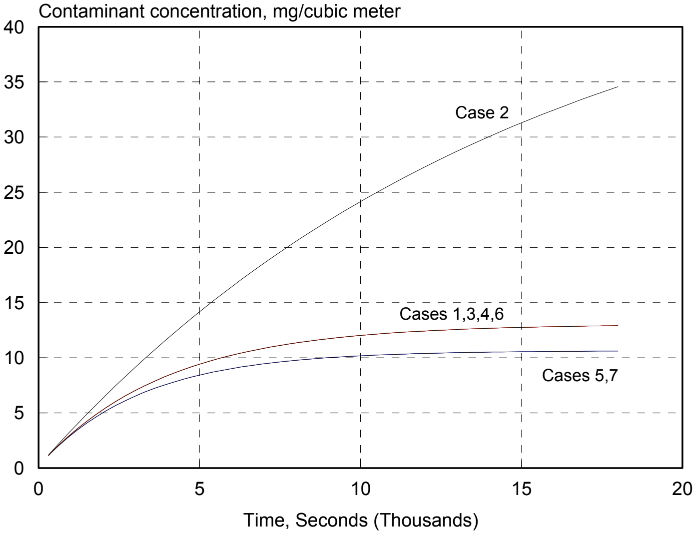

Figure *3* Concentration behavior of indoor contaminant at different filter arrangements when outdoor air is the source of contaminant

The least steady state contaminant concentration (i.e. 0.97 mg/m^3) is obtained in case 7 when filters are placed in three locations. However, when removing one filter from the re-circulated air path (case 6) no major changes in steady state contaminant concentration and time constant occur (C_i = 1.19 mg/m^3 τc = 3952 seconds). This indicates that placing two filters in parallel in the closed air circulation loop does not have a considerable impact on contaminant concentration transient behavior and steady state condition when the outdoor air is the source of the contaminant. However, the impact is more appreciable when the contaminant is generated indoors.

A comparison between cases 3, 4 and 6 reveals that the time constant is determined by the number of filters in the closed air circulation loop regardless of their location. On the other hand, contaminant concentration is significantly affected by filter location when outdoor air is the source of contaminant as can be seen when comparing cases 4 and 6. However, neither the time constant nor the contaminant concentration behavior is affected by filter placement in the closed air circulation loop when the contaminant is generated indoors, as can be seen from Figure *3* by comparing cases 1 and 3. Placing a filter after the mixing point in addition to the outside air filter performs better than replacing it in the re-circulated loop prior to the mixing point. Furthermore, a comparison between cases 3 and 4 reveals that placing the filter after the mixing point results in the same contaminant concentration behavior as placing two filters: one at the outside air and the other at the re-circulated air loop prior to the mixing point. The maximum time constant and concentration, when the outdoor air is the source of contaminant, occurs in case 2 when placing the filter outside the circulating air loop prior to the mixing point as can be depicted from *Table* 2. In this case, a very long period is needed for the process to reach steady state, which is reflective of the relatively large time constant. Not much reduction in the steady state concentration occurs when placing the filter in the re-circulating air stream (case 1), but a significant increase in the transient response is achieved as can be seen from *Figure 2*. It is clear that the filter placed inside the circulating air loop (case 1) accelerates the process of reaching the steady state conditions, but does not significantly contribute to the reduction in contaminant concentration as compared to case 2 in spite of the continuity of the contaminant removal process. This is due to the fact that when no outside air filter is used, the outdoor contaminant is directly introduced to the space and controls the contaminant mass built up and hence the level of concentration in the space.

The most improper placement of the filter is at the make up stream prior to the mixing point (case 2) when the contaminant is generated indoors, resulting in a contaminant concentration which is significantly higher compared to other cases, as illustrated in *Figure 3*. In this case, the exhaust air is the only balancing contaminant sink, without which there will be an unlimited increase in contaminant concentration.

5. CONCLUSION

Depending on the source of contaminant, filter placement in the air conditioning system plays a major role in determining contaminant transient and steady state concentration behavior. The optimal location of the filter is that which results in the least contaminant concentration at steady rate conditions and the fastest transient response (the least time constant), indicating quick contaminant removal action. When the outdoor air is the source of the contaminant and a single filter is to be used, the best location for the filter is at the mixing point. When an additional filter is to be placed in a different location, it should be placed in the outside make-up air prior to the mixing point. A third filter can be placed at the re-circulating air path. When the contaminant is generated indoors, the filter (s) can be placed anywhere in the closed air circulation loop. However, placing an outside air filter when the contaminant is generated indoors attains no benefit. The optimal filter location when contaminant sources are available indoors and outdoors is after the mixing point, if one filter is utilized. The second filter can be placed at the point of the make-up air intake and the third can be placed in the re-circulating air section. In general, if there are no practical and design constraints, placing additional filters (or more efficient filters) at the location of the optimal single filter would be the right choice.

ACKNOWLEDGMENT

The support and encouragement of KFUPM is highly appreciated.

Top

NOMENCLATURE

C_i = indoor contaminant concentration, mg/m^3

C_{io} = initial indoor contaminant concentration, mg/m^3

C_s = contaminant concentration in supply air, mg/m^3

C_o = contaminant concentration in outdoor air, mg/m^3

Q_s = supply air rate, m^3/s

Q_r = re-circulated air rate, m^3/s

Q_e = exhaust air rate, m^3/s

Q_o = outdoor or make up air rate, m^3/s

Q_{rn} = $Q_r + Q_e$ = return air rate, m^3/s

mc = *rate* of change of contaminant mass in indoor space, mg/s

N = contaminant generation rate, mg/s

V = space volume, m^3

t = time, s

α_r = percentage (by volume) of return air (or supply air) re-circulated to the space

η = filter efficiency, subscripts r, o, m denote the location of filter relative to the air stream.

REFERENCES

1. ASHRAE, 1996, HVAC Systems and Equipment-ASHRAE Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta, Georgia, USA.
2. Burroughs, H.E., 1999, “Improved Filtration and the Residential Environment: An Intervention Research Project to Determine the Relevancy and Efficacy of Particulate Filtration in Improving Air Quality Conditions in Residences”, Proceedings, IAQ and Energy 98-Using ASHRAE Standards 62 and 90.1, ASHRAE, pp 147-162, New Orleans, Louisiana, USA
3. Giles, J.H., 1987, “The Benefits of Using Filtered and Re-circulated Air as Ventilation Air”, Proceedings, IAQ 87-Practical control of indoor air problems USA, ASHRAE, pp 275-280, Arlington, Virginia, USA.
4. McQuiston, F.C. and Parker, J.D., 1988, Heating, Ventilating, and Air Conditioning- analysis and deign, 4th Edition, John Wiley& Sons, Inc.
5. Muller, C.O. and England, W.G., 1995, “Achieving Your Indoor Air Quality Goals-Which Filtration System Works Best?”, ASHRAE Journal, 37(2), pp 24-31.
6. Owen, M.K., 1993, “Relating Air Cleaner Efficiency to Indoor Air Quality”, Proceedings, IAQ 92-Environments for People, ASHRAE, pp 397-402, San Francisco, USA.
7. Schafer, N. and Kotz, D.A., 1987, “Successful Clean Room Design”, ASHRAE Journal, 29(9), pp 25-28.
8. Wilkinson, R.J., 2001, “Filter Performance Depends on Installation” HPAC Engineering, December, pp 51-53.

Top