J. KAPRA Vol. 11, No. E(1995) pp.45~54

The Impact of Ventilation Strategies on Indoor Air Pollution

- A Comparative Study of HVAC Systems Using a Numerical Model -

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Abstract

Indoor air quality models are useful to predict indoor air pollutant concentrations as a function of several indoor factors. Indoor air quality model was developed to evaluate the pollutant removal efficiency of variable-air-volume/bypass filtration system (VAV/BPFS) compared with the conventional variable-air-volume (VAV) system. This model provides relative pollutant removal effectiveness of VAV/BPFS by concentration ratio between the conventional VAV system and VAV/BPFS. The predictions agree closely, from 5 to 10 percent, with the measured values for each energy load. As a results, we recommend the VAV /BPFS is a promising alternative to conventional VAV system because it is capable of reducing indoor air pollutant concentration and maintaining good indoor air quality.

1. INTRODUCTION

Indoor air quality (IAQ) models are developed to aid in understanding and predicting indoor air pollutant concentrations as a function of outdoor air pollutant concentrations, indoor-outdoor air exchange rate, emissions from indoor sources, and indoor pollutant removal mechanisms (Austin *et al.* 1992). In general, IAQ models can be classified into two categories: (1) the mass balance theory, (2) statistical models based on regression analysis.

The mass balance equation involves indoor volume, indoor sources, sinks, flow rate such as make-up air, recirculation, infiltration, and filter efficiency. Turk (1963) introduced general IAQ equations in a single-chamber model. Moschandreas *et al.* (1985) suggest the general expression of the mass balance model to predict indoor pollutant concentration. Ott *et al.* (1988) use the SHAPE (Simulation of Human Activities and Pollutant Exposures) model to estimate the distribution of CO concentration in 22 micro-environments (e.g., garage, kitchen, school) based on monitored concentrations for one- or eight-hour periods for one day. Sparks (1988) provides the INDOOR model for analysis of the impacts of sources, sinks, HVAC (heating, ventilating, and air conditioning), and air cleaners on indoor pollutant concentrations.

This model focuses on emission factors such as cigarettes, kerosene heaters, and floor wax generally used for residential buildings. Hayes (1991) uses an indoor air quality model (IAQM) to estimate indoor ozone levels by micro-environment type (home, office, and vehicle) and configuration (windows open, windows closed, older construction, weatherized, and air conditioned). Similar mass balance equations have been applied by many researchers including Shair *et al.*(1974), Moschandreas and Stark (1978), Traynor *et al.*(1981) and Ishizu (1980) to predict indoor air pollutants.

The other approach for predicting indoor pollutant concentrations is based on statistical methods. A regression analysis, including multilinear regression techniques, is used in indoor statistical models. An example of this approach is given by Drye (1989). A statistical model was developed using linear regression analysis to predict indoor concentrations of nitrogen dioxide based on 1950 survey data. The empirical model employed multi-linear regression techniques and data from five U.S. metropolitan areas. The results of this study indicated that ambient NO_2 levels alone explain an estimated 37 percent of the variability in indoor NO_2 level. Given sufficiently large data bases, statistical models may be used to predict indoor pollutant concentrations under a wide range of conditions.

The purpose of this paper is to develop a mathematical model simulating the performance of both systems, VAV and VAV/BPFS system. This paper is focused on the impact of VAV/BPFS depending on the various outdoor supply air flow rates, and ventilation effectiveness.

2. MATERIALS AND METHODS

All experiments were carried out in an environmental chamber with an 32.6 m^3 all-aluminum structure capable of controlling temperature, relative humidity, air recirculation rate, and air exchange rate. Air enters the chamber through a uniformly porous ceiling and flows laminarly to the floor. Performance of this study required that pollutant sources emit into the chamber. A spray deodorant container was used as a source of TVOC (total volatile organic compound). To avoid different emission rates, the same brands of deodorant and cigarette were used for all experiments. Typically, a spray episode was used to reach, steady state level, predetermined TVOC levels (15.9 and 19.1 mg/m^3 as a benzene) of pollutants. Energy loads are needed in the chamber to induce operation of the ventilation system. The chamber setpoint temperature in this study was 24°C for all experiments. When the chamber temperature rose above 24°C, the ventilation system began operating to cool the chamber.

The energy loads used in this study were 400, 800, 1200, and 1900 watts. The energy loads in the chamber were generated by commercial 200 watt light bulbs. Each of the various energy loads leads to different ventilation rates.

The pollutant concentration measuring instruments, TVOC analyzer (HNU Model PI 101 trace gas analyzer, HNU system), were put together in an assembly for easy access. For quality control for this analyzer, zero span control was performed daily before starting the experiments. Energy variables were measured from precise temperature (Model CT-830-D, Hy-Cal Engineering) and flow rate (Magnehelic Air Filter Gages, Dwyer) instruments at predetermined sites within the chamber. Additionally, the temperature of an indoor and an outdoor site were measured, and recorded by a computer, to set the operation of the HVAC system. The sampling instruments were placed outside chamber.

2.1 HVAC Systems

The chamber ventilation system could operate with either of two types of HVAC system: VAV (variable-air-volume) system or VAV/BPFS (variable-air-volume/bypass filtration system). The VAV system responds to indoor temperature measured by a thermostat inside the chamber, i.e., it begins operating after the in-chamber temperature reaches a certain level (24°C) which is referred to as the setpoint temperature. The VAV/BPFS in addition to responding to an indoor thermostat and the level of pollutant concentrations. The Star Zone Master 3000 Climate Control System (SZM 3000) (Zone-all Control Systems Inc.) was used in conjunction with a filtration system to affect energy savings by reducing the flow of outdoor air, and to improve IAQ by reducing indoor air pollutant concentrations.

Fig. 1 shows the test HVAC system corresponding with the VAV mode and the VAV/BPFS mode. The test system utilizes two thermostats: T1 inside the chamber and T2 outside the chamber. A 12-inch AVD (Air Volume Damper) zone damper is used to control the air flow by electronic controller responded to T1. T2 is an input value to the system to create heating or cooling demands on the system. The cooling air is supplied to the test chamber via cold water coils controlled by valves V1 and NV1. These valves are energized by the SZM 3000. The 10-inch RAD (Relief Air Damper) bypass damper opens and closes with changes in the static pressure in the supply duct to the test chamber. The 12-inch AVD filter damper of the VAV/BPFS is controlled by the IAQ sensor, and opens or closes on demand as required by the level of the chamber air quality. Thus, the operational difference of the VAV and the VAV/BPFS system was determined by whether the IAQ sensor was used or not. If the IAQ sensor was used, the system operated in the VAV/BPFS mode; otherwise the system operated in the VAV mode.

3. MODEL DEVELOPMENT

A pictorial model of VAV/BPFS system with auxiliary VAV bypass loop is shown in Fig. 2. A mass balance model was formulated to calculate contaminant concentrations in the occupied space where contaminant is generated, removed, or added by sources and/or air flows. Note two space volumes are to be considered; V (chamber volume), (total system volume) which is the summation of chamber volume and the volume of the HVAC system.

The rate of change in the total mass contaminant in the chamber volume V is expressed

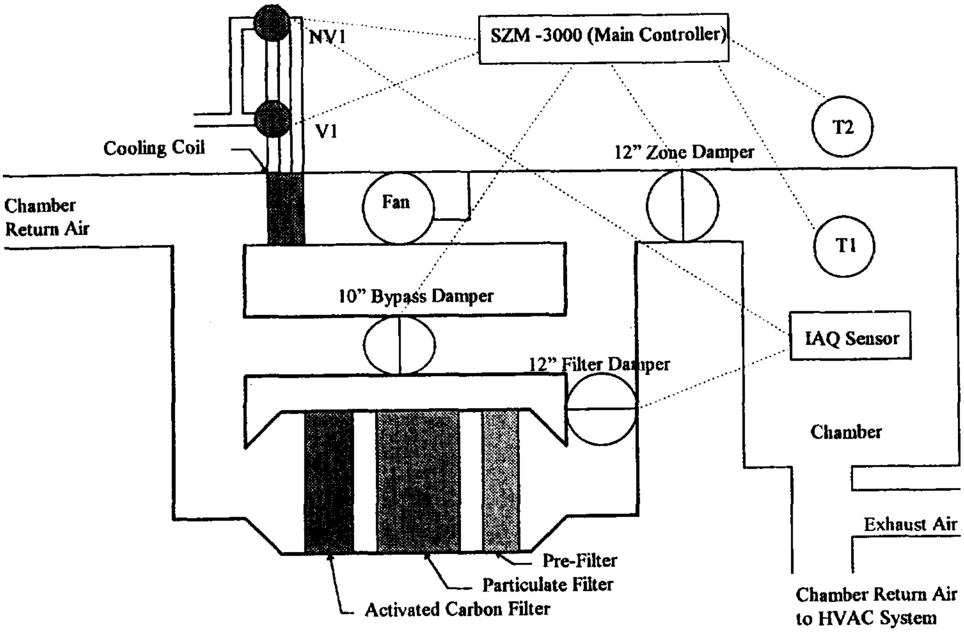

Fig. 1. Variable-air-volume/bypass filtration system.

by

$$V\frac{dC}{dt}=\dot{M}_{generated}+\dot{M}_{entered}-\dot{M}_{removed} \tag{1}$$

where V represents indoor chamber volume (volume), C pollutant concentration (mass/volume), $\dot{M}_{generated}$ indoor source emission rate (mass/time), $\dot{M}_{\mathrm{entered}}$ pollutant concentration added by supply air (mass/time), removed pollutant concentration removed by air flows and filtration (mass/ time), and t time (time).

The outdoor supply air enters with rate Q_o from outdoor and passes through a filter with efficiency ($E_{f,o}$). Total system air flow (outdoor supply air+return air+bypass recirculated air) passes through system filter with efficiency (E_f) at a rate Q, while the bypassed recirculated air passes through an additional filter, the bypass filter with efficiency ($E_{f,b}$), at a rate Q_b. Filter efficiency ($E_{f,o}$, E_f, and $E_{f,b}$) is characterized by the following equation: filter efficiency=$(C_{\mathrm{inlet}}-C_{\mathrm{outlet}})/C_{\mathrm{inlet}}$, where C_{inlet} is the pollutant concentration in the air flow just prior to the filter, and C_{outlet} that in the air flow leaving the filter.

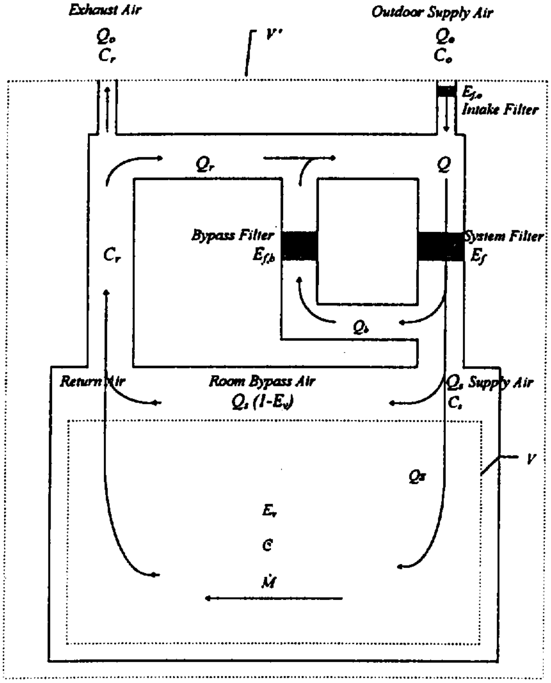

Fig. 2. Modeling of VAV/BPFS System.

For VAV/BPFS system, the appropriate starting equation is:

$$V\frac{dC}{dC}=\dot{M}+[C_rQ_r+C_sQ_b(1-E_{f,b})+C_oQ_o(1-E_{f,o})](1-E_f)E_v-CQ_sE_v \tag{2}$$

where $\dot{M}$ is indoor source emission rate (mass/time), C concentration of the chamber (mass/volume), C_o concentration of outdoors (mass/volume), C_r concentration of return air (mass/volume), C_s concentration of supply air (mass/volume), Q_o outdoor supply air flow rate (mass/volume), Q total system flow rate (volume/time), Q_b bypass recirculated air flow rate (volume/time), $E_{f,o}$ filter efficiency of outdoor supply air (dimensionless fraction), E_f system filter efficiency (dimensionless fraction), $E_{f,b}$ bypass filter efficiency (dimensionless fraction), and E_v ventilation effectiveness (dimensionless).

Equation 2 is rearranged as follows:

$$V\frac{dC}{dC}+CQ_sE_v=\dot{M}+[C_rQ_r+C_sQ_b(1-E_{f,b})+C_oQ_o(1-E_{f,o})](1-E_f)E_v \tag{3}$$

The steady-state solution of this first order mass-balance differential equation results in Equation 4. The variables involved are chamber concentration, volume size and ventilation rate.

$$C_{ss}=\frac{\dot{M}+[C_rQ_r+C_sQ_b(1-E_{f,b})+C_oQ_o(1-E_{f,o})](1-E_f)E_v}{Q_sE_v} \tag{4}$$

where C_{ss} is steady-state concentration in chamber (mass/volume). The contaminant concentration in the return air duct, C_r, is obtained from similar considerations of mass balance of the total system volume V'. The rate of change of C_r with time, is given by the following equation.

$$V'\frac{dC_r}{dC}=\dot{M}+C_oQ_o(1-E_{f,o})(1-E_f) \quad (5)$$
$$-C_r(Q_o+Q_rE_f)-C_sQ_b[E_{f,b}+(1-E_{f,b})E_f]$$

where C_s can be found by taking the mass-balance equation around the system filter:

$$C_sQ=[C_rQ_r+C_sQ_b(1-E_{f,b})+C_oQ_o(1-E_{f,b})](1-E_f) \quad (6)$$

or

$$C_s=\frac{[C_rQ_r+C_oQ_o(1-E_{f,b})](1-E_f)}{Q-Q_b(1-E_{f,b})(1-E_f)} \quad (7)$$

Substitute of C_s from equation 7 into equation 5 and get

$$V'\frac{dC_r}{dt}+C_r\left\{(Q_o+Q_rE_f)+\frac{Q_rQ_b(1-E_f)[E_{f,b}+(1\text{-}E_{f,b})E_f]}{Q-Q_b(1-E_{f,b})(1-E_f)}\right\}$$
$$=\dot{M}+C_oQ_o(1-E_{f,o})(1-E_f)$$
$$-\frac{Q_bC_oQ_o(1-E_{f,o})(1-E_f)[E_{f,b}+(1-E_{f,b})E_f]}{Q-Q_b(1-E_{f,b})(1-E_f)} \quad (8)$$

The steady-state solution of this first order mass-balance differential equation is

$$C_r=\frac{\dot{M}[Q\text{-}Q_b(1\text{-}E_{f,b})(1\text{-}E_f)]+C_oQ_o(Q\text{-}Q_b)(1\text{-}E_{f,o})(1\text{-}E_f)}{(Q\text{-}Q_b)[Q_o+Q_bE_{f,b}(1\text{-}E_f)+(Q\text{-}Q_o)E_f} \quad (9)$$

C_s in equation 4 is eliminated using equation 7.

$$C_{ss}=\frac{\dot{M}+[C_rQ_r+C_oQ_o(1-E_{f,b})]\left[\frac{Q(1-E_f)E_v}{Q-Q_b(1-E_{f,b})(1-E_f)}\right]}{Q_sE_v} \quad (10)$$

Finally, C_r is eliminated by the substitution of equation 9 into equation 10. The steady state concentration (C_{ss}) in chamber for VAV /BPFS system is determined to equation 11.

$$C_{ss,VAV/BPFS}=\frac{\dot{M}K+C_oQ_o(1-E_{f,o})(1-E_f)\left(\frac{Q}{Q-Q_b}\right)}{Q_o+Q_bE_{f,b}(1-E_f)+(Q-Q_o)E_f} \quad (11)$$

where $C_{ss,VAV/BPFS}$ shows steady state concentration in chamber with the VAV/BPFS system (mass/volume) and K represents as follows.

$$K=\frac{\left(1\text{-}\frac{Q_b}{Q}\right)\left[\frac{Q_o}{Q}+\frac{Q_b}{Q}E_{f,b}(1-E_f)+\left(1\text{-}\frac{Q_b}{Q}\right)E_f+(1-E_f)E_v\right]\text{-}\frac{Q_b}{Q}(1-E_f)E_v}{\left(1-\frac{Q_b}{Q}\right)^2E_v}$$

For the conventional VAV system, which may be thought of as system with a VAV bypass loop, but without bypass filtration system, $E_{f,b}=0$, then equation 11 becomes the equation 12:

$$C_{ss,VAV}=\frac{\dot{M}K+C_oQ_o(1-E_{f,o})(1-E_f)\left(\frac{Q}{Q-Q_b}\right)}{Q_o+(Q-Q_o)E_f} \quad (12)$$

where $C_{ss},_{VAV}$ is steady state concentration in breathing zone using the VAV system (mass /volume) and K follows as:

$$K=\frac{\left(1\text{-}\frac{Q_b}{Q}\right)\left[\frac{Q_o}{Q}+\left(1\text{-}\frac{Q_b}{Q}\right)E_f+(1-E_f)E_v\right]\text{-}\frac{Q_o}{Q}(1-E_f)E_v}{\left(1\text{-}\frac{Q_b}{Q}\right)^2E_v}$$

It is of interest to assess the VAV bypass (with or without bypass filtration system) on the indoor air quality in occupied space by comparing equations 11 and 12.

If the contaminant concentration from outdoors is negligible, $C_oQ_o=0$, in comparison with the indoor concentration, then equation is simplified to

$$\frac{C_{ss,VAV/BPFS}}{C_{ss,VAV}}=\frac{\dfrac{\frac{Q_o}{Q}+\frac{Q_b}{Q}E_{f,b}(1-E_f)+E_f-\frac{Q_o}{Q}E_f+(1-E_f)E_v}{\frac{Q_o}{Q}+\frac{Q_b}{Q}E_{f,b}(1-E_f)+E_f-\frac{Q_o}{Q}E_f}}{\dfrac{\frac{Q_o}{Q}+E_f-\frac{Q_o}{Q}E_f+(1-E_f)E_v}{\frac{Q_o}{Q}+E_f-\frac{Q_b}{Q}E_f}} \quad (13)$$

Since contaminant generation rate ($\dot{M}$) is constant and equal for both systems, equation 13 does not include $\dot{M}$ term. However, it is a function of many variables such as outdoor air fraction (Q_o/Q), bypass air flow fraction (Q_b/Q), main system filter efficiency (E_f), bypass filter efficiency ($E_{f,b}$), and ventilation effectiveness (E_v).

As stated earlier, the outdoor supply air flow rate of both systems is a function of the supply air temperature. Under the controlled chamber conditions, the relationship of outdoor supply air ratio is expressed by the following equation:

$$\left(\frac{Q_o}{Q}\right)_{VAV} \times (T_{in}-T_{SA,VAV}) = \left(\frac{Q_o}{Q}\right)_{VAV/BPFS} \times (T_{in}-T_{SA,VAV/BPFS}) \tag{14}$$

where $(Q_o/Q)_{VAV}$ is outdoor supply air ratio of the VAV system (dimensionless), $(Q_o/Q)_{VAV/BPFS}$ outdoor supply air ratio of the VAV/BPFS system (dimensionless), T_{in} indoor temperature (°C), $T_{SA,VAV}$ supply air temperature of the VAV system (°C), and $T_{SA,VAV/BPFS}$ supply air temperature of the VAV/BPFS system (°C).

or

$$\left(\frac{Q_o}{Q}\right)_{VAV/BPFS} = \left(\frac{Q_o}{Q}\right)_{VAV} \times \frac{(T_{in}-T_{SA})_{VAV}}{(T_{in}-T_{SA})_{VAV/BPFS}} \tag{15}$$

Let $\dfrac{(T_{in}-T_{SA})_{VAV}}{(T_{in}-T_{SA})_{VAV/BPFS}} = \Delta T_R$,

where T_R is ratio of temperature difference of the two systems

So, equation 15 can be expressed by the following equation:

$$\left(\frac{Q_o}{Q}\right)_{VAV/BPFS} = \left(\frac{Q_o}{Q}\right)_{VAV} \times \Delta T_R \tag{16}$$

Substitute $(Q_o/Q)_{VAV/BPFS}$ from equation 16 into equation 13 and to get

$$\frac{C_{ss,VAV/BPFS}}{C_{ss,VAV}} = \frac{\dfrac{\Delta T_R \dfrac{Q_o}{Q} + \dfrac{Q_b}{Q} E_{f,b}(1-E_f) + E_f - \Delta T_R \dfrac{Q_o}{Q} E_f + (1-E_f)E_v}{\Delta T_R \dfrac{Q_o}{Q} + \dfrac{Q_b}{Q} E_{f,b}(1-E_f) + E_f - \Delta T_R \dfrac{Q_o}{Q} E_f}}{\dfrac{\dfrac{Q_o}{Q} + E_f - \dfrac{Q_o}{Q} E_f + (1-E_f)E_v}{\dfrac{Q_o}{Q} + E_f - \dfrac{Q_b}{Q} E_f}} \tag{17}$$

During all experiments under the same controlled conditions, the temperature ratio, T_R, is always less than 1. This is because the sensible cooling load for each system and the corresponding indoor temperature are constant and equal but the supply air temperature for the VAV/BPFS system is lower than that of the VAV system. Therefore, the outdoor supply air flow rate of the VAV/BPFS system reduces by T_R. The lower T_R value, the lower outdoor supply air flow rate of the VAV/BPFS system.

4. RESULTS AND DISCUSSIONS

The model of conventional VAV system would include ventilation with outdoor air, main system filter efficiency, and ventilation effectiveness. The model of VAV/BPFS system includes these components plus the bypass filter efficiency. Thus, the model difference of the two ventilation systems focuses on whether or not the bypass filter is included. If there is no bypass filter, then the concentration ratio is higher than 1 due to reduction of outdoor supply air for VAV/BPFS system. With the bypass filter, the concentration ratio decreases.

The results of equation 18 are plotted in Fig. 3 and 4 for the case with system filter efficiency of zero percent (this is the case for the experiments performed because the chamber did not include intake filter and system filter, it only used the bypass filter) and ventilation effectiveness of 0.65 (typical office) and 1.0 (perfect mixing), and bypass filtration effici-

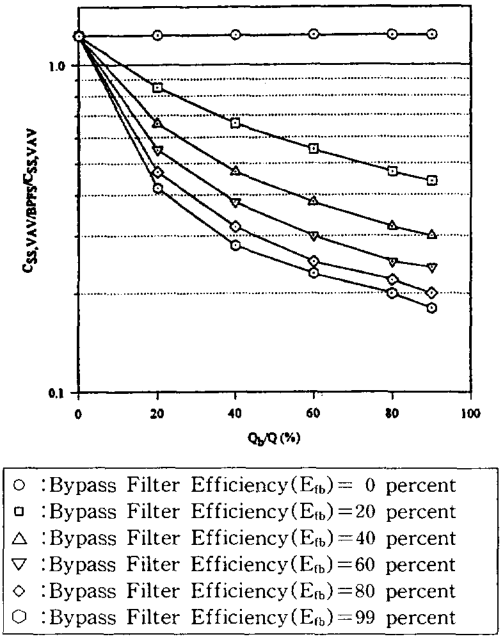

Fig. 3. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.1, T_R=0.8, E_v=1, and E_f=0 percent.

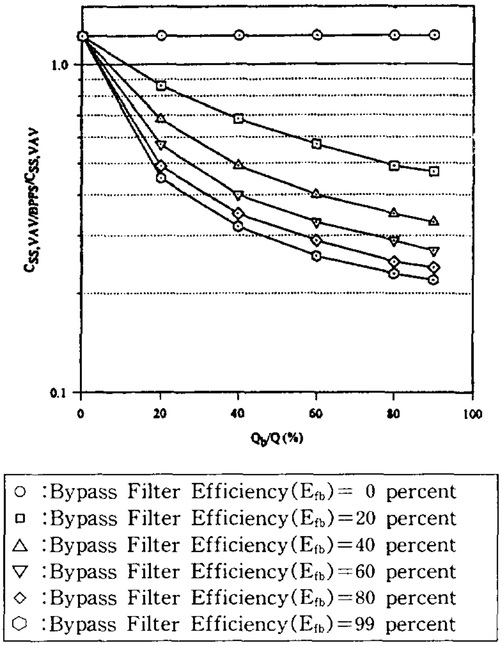

Fig. 4. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.1, T_R=0.8, E_v=0.65, and E_f=0 percent.

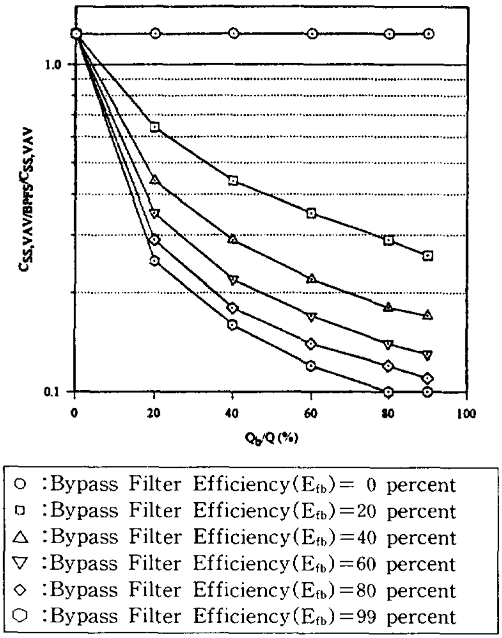

Fig. 5. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.05, T_R=0.8, E_v=1, and E_f=0 percent.

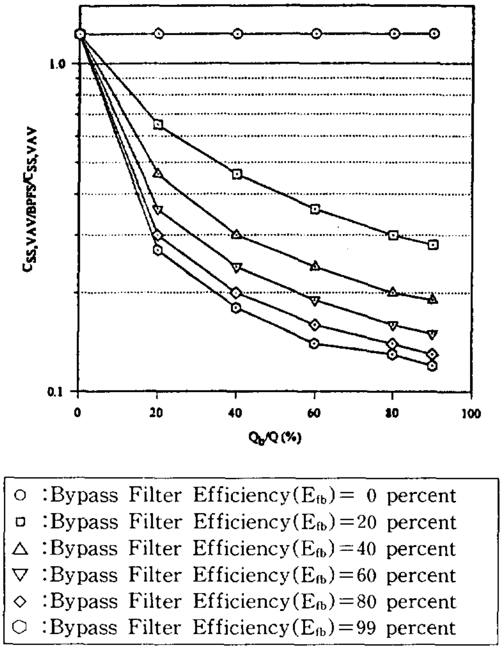

Fig. 6. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.05, T_R=0.8, E_v=0.65, and E_f=0 percent.

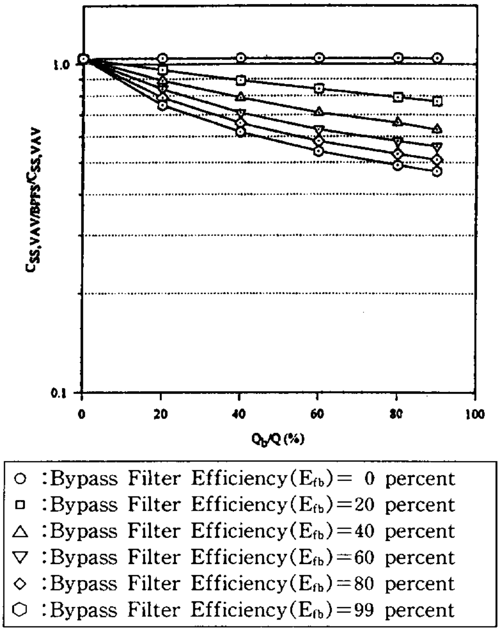

Fig. 7. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.1, T_R=0.8, E_v=1, and E_f=20 percent.

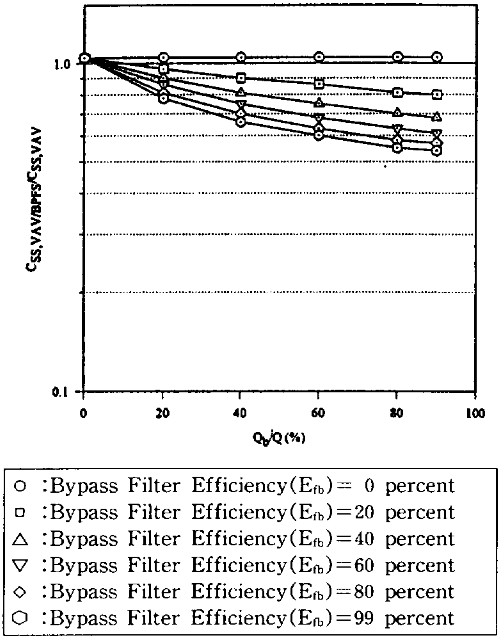

Fig. 8. Effect of VAV-bypass filter on indoor air quality with Q_o/Q=0.1, T_R=0.8, E_v=0.65, and E_f=20 percen.

ency between 0 and 99 percent and T_R, 0.8 (which corresponds data results). Fig. 5 and 6 show effect of VAV-bypass filter on indoor air quality with reduction in the outdoor supply air to 5 percent. Reduction of outdoor supply air results in decreased dilution removal rate and on increased bypass filtration removal rate with the VAV/BPFS system. Fig. 7 and 8 show the effect of VAV-bypass filter on indoor air quality with 10 percent outdoor supply air, T_R=0.8, 20 percent HVAC system filter efficiency (E_f), and ventilation effectiveness 1 and 0.65, respectively. With HVAC system filter, the bypass filter removal on indoor air quality would be decreased according to the system filter efficiency. Thus, if the filter efficiency of an HVAC system is already high, the addition of a high-efficiency filter in the bypass filtration system would not help much in improving the IAQ of the occupied zone. However, for the building with a low-efficiency HVAC system filter, the addition of filters in the bypass filtration system improve the IAQ substantially as shown in Fig. 3 and 4. All experiments were performed in a chamber under the following controlled conditions: (1) pollutant emission rate is constant and does not vary from experiment to experiment, and (2) energy loads are constant for each series of experiments, but vary from series to series experiments. Indoor air quality model ratio predictions of both systems, equation 18, are compared with the corresponding measured ratio of conventional VAV and VAV/BPFS systems. Indoor air quality model comparison of the TVOC predictions versus measured val-

Table 1. Comparison of Predicted versus measured TVOC concentration ratios for corresponding VAV and VAV/BPFS system value.

Energy Load	Predicted Ratio	Measured Ratio
400W	0.63±0.03*	0.66±0.06
800W	0.60±0.02	0.65±0.09
1200W	0.59±0.03	0.64±0.08
1900W	0.56±0.02	0.63±0.10

ues is shown in Table 1. The predictions agree closely (from 5 to 10 percent) with the measured values for each energy load.

Clearly this model results do support the IAQ benefits of using a demand control removal strategy. Retrofitting the VAV system with the VAV/BPFS system was easy. The use of VAV/BPFS system is, therefore, recommended for buildings with VAV system as well as for buildings under construction. The evidence used for these conclusions is from controlled chamber experiments, a series of before and after retrofit experiments in office buildings would be required to further substantiate the new system that has the potential to reduce indoor air pollution cost effectively.

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실내오염물질의 환기기술전략에 따른 영향평가

- 수치적 모델을 이용한 HVAC 시스템의 비교연구 -

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초 록

실내공기질 모델은 실내공기오염물의 예측과 오염원의 발생정도을 알기 위해 유용하게 쓰여진다. 본 연구는 기존의 환기시스템인 VAV (Variable-Air-Volume) 시스템을 기반으로 실내공기질 모델을 개발하고 새 VAV/BPFS (Variable-Air-Volume/Bypass Filtration Sys-tem)와 비교분석함으로써 새 환기시스템의 유용성과 효율성을 증명하고자 하였다. 본 연구는 32 m^3의 알루미늄 chamber에서 수행하였으며, 이 chamber는 온도, 습도 및 유량(air exchange rate)을 조절할 수 있도록 설계

되어 있다. 본 연구에서 개발된 VAV/BPFS는 chamber에 맞도록 구조 및 설계를 변경하였으며, 기존의 시스템 mode와 VAV/BPFS mode로 선별적으로 작동하도록 하였다. 본 실험 모델은 제어된 동일한 조건하에서 두 환기시스템을 작동하여 TVOC (Total Votaile Organic Compound) 농도를 관찰 후 실험 농도와 모델에 의한 예측 농도와 비교 분석함으로서 모델의 타당성을 증명했다. 본 연구 모델은 기존의 환기시스템에 활성탄 필터 (activated carbon filter)를 설치함으로서 Bypass Filtration의 영향을 평가하였으며, 인체에 유해한 유기물 (TVOC)의 제거효율성을 조사 분석하였다. 본 모델은 실험농도치와 예측 농도치 간의 오차가 평균 5에서 10 퍼센트로 TVOC의 농도를 효과적으로 예측하였으며, 여러 인자에 따른 예측 농도를 제시함으로서 VAV/BPFS 시스템에 대한 기초적 자료를 제공할 것이다.