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HVAC air-quality model and its use to test a $PM_{2.5}$ control strategy

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Abstract

This paper presents a MATLAB® Simulink air-quality model of a commercial building with a heating, ventilation, and air conditioning (HVAC) system in Fairbanks, Alaska. Outdoor and indoor real-time fine particulate matter ($PM_{2.5}$) levels were measured at this building during a summer wild-fire smoke episode and then during a winter period. The correlation coefficient between the model-predicted and the measured indoor concentrations was 0.99 for the summer and 0.98 for the winter, justifying the usability of the model for further studies. An HVAC control algorithm was developed that reduces the indoor $PM_{2.5}$ levels. The algorithm was tested using the HVAC Simulink model and the outdoor $PM_{2.5}$ data from the summer smoke episode. The average indoor $PM_{2.5}$ level with this control algorithm was 65% lower than with the regular control. Thanks to the $PM_{2.5}$ control strategy being automatically engaged only during episodes, it was shown to have the potential of significantly reducing the indoor $PM_{2.5}$ levels without significantly compromising the purpose of the original control strategy.

Keywords: Air quality; Particulates; HVAC; Control; MATLAB® Simulink; Model

1. Introduction

Fairbanks experiences strong ground-based temperature inversions in the wintertime [1]. As a result, pollutants released into the air accumulate close to the ground and their concentrations can reach high levels [2]. Carbon monoxide (CO) and particulate matter (PM) are especially of concern. In the summertime, forest fires in Alaska can cause high concentrations of PM in Fairbanks. PM is known to have a negative effect on human health [3] and recent studies have shown that fine particles have a higher impact than coarse particles because they penetrate deeper into lungs. Fine particles are defined as those with the aerodynamic diameter of 2.5 μm and less ($PM_{2.5}$). Because of new findings related to the health effects of $PM_{2.5}$ [3], the US Environmental Protection Agency decreased the 24-h standard for ambient air from 65 to 35 μg/m^3 in September 2006. In Fairbanks, the winter $PM_{2.5}$ levels are known to exceed 35 μg/m^3, and the summer levels caused by wild fires in close-by regions of Alaska have reached over 1000 μg/m^3 in the past.

People in the United States spend approximately 90% of their time indoors [4]. This percentage is expected to be even higher in Fairbanks in the wintertime and also during summer smoke episodes. This demonstrates the importance of the capability of building envelopes and ventilation systems to protect the inhabitants from outdoor air pollution. However, the design of many ventilation systems assumes that the outdoor air is clean. One of the control strategies is known as the demand control ventilation (DCV) where the ventilation rate is usually based on the carbon dioxide (CO_2) level, which is used as an occupancy indicator. This strategy assumes that the human activity is the primary source of indoor pollution and that by increasing the ventilation rate, the polluted air is replaced by the outdoor clean air. This strategy can have a negative effect on human health, though, if the outdoor air is strongly polluted.

Green et al. [5] looked at several control strategies to decrease the indoor levels of CO. One of the strategies, in a

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simplified way, used an outdoor and indoor CO sensor and set the ventilation rate to low when the outdoor CO level was higher than the indoor one and set the ventilation rate to high when the indoor CO level was higher than the outdoor one. This strategy decreased peaks in the indoor CO concentration during busy traffic hours, which decreased the mean CO concentration by 34%.

CO is a relatively stable gas with a lifetime in the atmosphere of approximately 2 months [6]. Therefore, its concentration is practically not affected by contact with indoor surfaces or by penetration through filters. The situation is different, though, with $PM_{2.5}$, which is deposited on indoor surfaces and filters of ventilation systems. This allows for a different approach for controlling the indoor concentration. One possible control strategy focused on reducing the indoor $PM_{2.5}$ levels is described in this paper. The strategy was tested using a MATLAB® Simulink model of a heating, ventilation, and air conditioning (HVAC) system for a commercial building in Fairbanks, Alaska. Measured $PM_{2.5}$ data verifying the plausibility of the model is also presented in this paper.

2. Methods

2.1. Data collection

Two useful data sets were obtained at a campus building of the University of Alaska Fairbanks during July 2005 and December 2006. The measurement in July 2005 was performed during a part of an episode with elevated $PM_{2.5}$ levels caused by a wild fire in a close-by region of Alaska. The real-time $PM_{2.5}$ concentrations were measured simultaneously in an office and outside the building for a period of two days. Two TSI 8520 DustTraks were used for the $PM_{2.5}$ measurements. The outdoor DustTrak was placed in a portable environmental enclosure with a heater and a thermostat (set to 21 °C). The outdoor air was brought to the DustTrak via a piece of tubing. The logging interval was set to 2 min, but, in the end, the data were converted into 10-min averages. Outdoor and indoor real-time CO_2 data were collected using two TSI 8551 Q-Traks to shed light on the building ventilation rate. Real-time outdoor elemental carbon levels were measured using a Magee Scientific AE-21 Aethalometer. Outdoor temperature was measured using a HOBO H08-002-02 data logger with a TMC6-HA sensor.

The DustTrak uses a laser photometer to estimate the $PM_{2.5}$ concentration. The advantage of this method is that it provides real-time data, but the disadvantage is that the measured value depends on the reflective and other properties of the measured dust. Therefore, correction factors were applied to the DustTrak values. The correction factors were based on our side-by-side measurement during another wild-fire smoke episode earlier that summer. In this side-by-side measurement, a DustTrak was deployed next to a Met One BAM-1020 at the permanent monitoring station in Fairbanks. The DustTrak correction factor as a function of the DustTrak reading is shown in Fig. 1. It should be noted that this method yields just an approximation of the $PM_{2.5}$ data because the characteristic of the smoke can vary from one event to another, and also, the characteristic of the indoor $PM_{2.5}$ is different from that outdoor because it is modified by the HVAC filters and other components.

The setup of the measurement in December 2006 was similar to the one in July 2005. DustTraks were used to measure the real-time outdoor and indoor $PM_{2.5}$ levels. An SKC 761-203A personal environmental monitor (PEM) with an SKC 224-PCXR4 pump was used outdoors and an MSP 400 micro-environmental monitor (MEM) indoors for the collection of $PM_{2.5}$ on 0.8 μm polycarbonate filters. The correction of the DustTrak data was done using the average $PM_{2.5}$ concentrations found by the gravimetric analyses of the filters. These values were compared with the average $PM_{2.5}$ concentrations found by the DustTraks and correction factors were determined; as a result, all outdoor DustTrak data was multiplied by the correction factor of 0.31 and all indoor data by 0.39. For these $PM_{2.5}$ data, it was not possible to use the DustTrak correction curve that was used for the July 2005 data because, as mentioned earlier, the DustTrak correction factors depend on the characteristics of the measured $PM_{2.5}$, and the characteristics of the winter $PM_{2.5}$ were expected to be different from those for wild-fire smoke. Since the HVAC system of the studied building uses direct digital control (DDC), it was possible to record the system's variables in 10-min intervals. The variable of main interest was the position of the outdoor/recirculated air damper but other variables were also recorded, such as the fan speed, return air temperature, and mixed air temperature.

2.2. Modeling

The presented model can be used for any pollutant. But, since our study was focused strictly on $PM_{2.5}$, the term "$PM_{2.5}$" will be used instead of "pollutant" for better

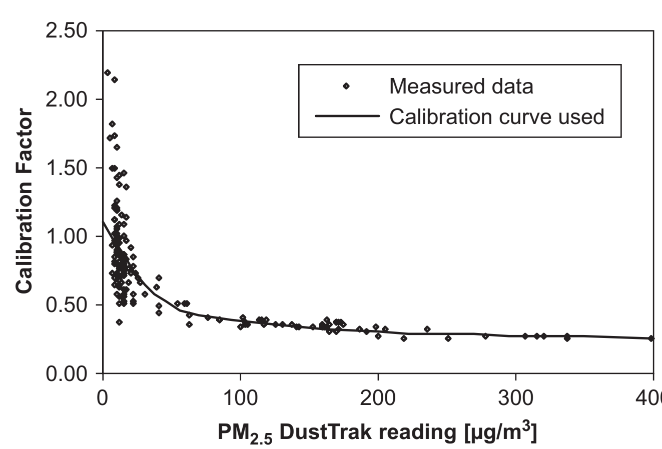

Fig. 1. DustTrak calibration factor as a function of DustTrak reading as determined by a side by side test with BAM 1020 during wild fire smoke.

clarity. The schematic of the HVAC system of the studied building is shown in Fig. 2, where Q_a is the ambient air flow, Q_r is the recirculated air flow, $Q = Q_a + Q_r$ is the total air flow of the air handler, c_a is the ambient concentration of $PM_{2.5}$, c is the indoor concentration of $PM_{2.5}$, V is the building volume, $m = Q_a/Q$ is the mixing ratio, and p is the penetration factor of the HVAC filter. It is assumed that all the air entering the building is passing through the HVAC system; the infiltration through the building envelope is neglected. Assuming a single-zone situation and a perfect mixing of the air within the zone, the relationship between the real-time indoor $PM_{2.5}$ concentration and the outdoor $PM_{2.5}$ concentration can be derived using a mass balance equation

$$dc/dt = R_{supply} - R_{removal}, \tag{1}$$

where R_{supply} is the $PM_{2.5}$ supply rate and $R_{removal}$ is the $PM_{2.5}$ removal rate. R_{supply} can be expressed as

$$R_{supply} = pk_v(1-m)c + pk_v m c_a + s, \tag{2}$$

where $k_v = Q/V$ is the air handling rate, and s is the indoor source strength. The term $pk_v(1-m)c$ represents the rate of $PM_{2.5}$ supply through the recirculated air, the term $pk_v m c_a$ represents the rate of $PM_{2.5}$ supply through the outdoor air intake, and s represents the rate of $PM_{2.5}$ supply via indoor sources. The $PM_{2.5}$ removal rate can be expressed as

$$R_{removal} = k_v c + (k + k_d)c, \tag{3}$$

where k is the decay rate (representing the rate of decay through chemical transformations), and k_d is the rate of deposition on surfaces (representing the rate of gravitational settling and other deposition mechanisms). The term $k_v c$ represents the rate of $PM_{2.5}$ removal through the outgoing air, and the term $(k+k_d)c$ represents the rate of $PM_{2.5}$ removal via deposition and decay. Combining Eq. (1), Eq. (2), and Eq. (3) results in the relationship

$$dc/dt = [pk_v(1-m) - k_v - (k + k_d)]c + pk_v m c_a + s. \tag{4}$$

It should be pointed out that the studied building has many individual rooms, which may seem to be in contradiction with the use of the single-zone model. However, using a multi-zone model would be impractical because of its complexity and the large number of unknown parameters. Assuming the air handling, decay, and deposition rates are similar in each room, the multi-zone model can be approximated with a single-zone model.

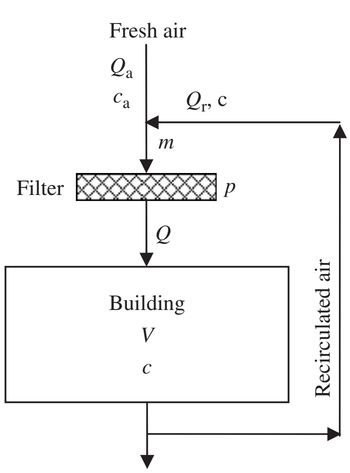

Fig. 2. Schematic of the HVAC system.

The control system of the HVAC system of the studied building maintains constant pressure in the ducts. This results in relatively constant air flow through the air handler and thus a relatively constant air handling rate. It should be emphasized that, as defined earlier, the air handling rate k_v represents the rate of exchange of the air through the air handler, which is not necessarily the same as the fresh-air ventilation rate because the air passing through the air handler is in general a mixture of the fresh air and recirculated air. Based on the data provided to us by the HVAC technicians, the air handling rate of the studied building is about $6\,h^{-1}$. The deposition rate of $PM_{2.5}$, k_d, can vary in a wide range [7], depending on many factors, such as the volume-to-surface ratio and the $PM_{2.5}$ characteristics. However, the majority of studies showed it to be well below $1\,h^{-1}$ [8–10]. It is a small value with respect to the air handling rate, and therefore, the knowledge of the exact value is not critical for our modeling purposes. The value of $k_d = 0.2\,h^{-1}$ was chosen for our model, which is a value used by Henderson et al. [11] for modeling the deposition of $PM_{2.5}$ produced by wild fires and prescribed burns. The decay rate of $PM_{2.5}$, k, can be assumed to equal $0\,h^{-1}$ because the rate of the decay of $PM_{2.5}$ through chemical transformations is negligible with respect to the rate of other removal mechanisms (deposition and air exchange). The indoor source strength is assumed negligible. Smoking is not allowed in the studied building. The other main indoor source of $PM_{2.5}$ is usually cooking [7], but it is normally not present in office environments. Therefore, $s = 0\,\mu g/m^3$-h was used for our model.

The minimum efficiency reporting value (MERV) value of the HVAC filter in the studied building is 13. Kowalski and Bahnfleth [12] presented a model for the filtering efficiency as a function of particle size. For MERV 13, the lowest efficiency of about 40% occurs for the particles of about $0.2\,\mu m$ size. The efficiency is higher for particles smaller than that because of the effect of Brownian motion, and it is also higher for particles bigger than that because of interception. This implies that the penetration factor p for $PM_{2.5}$ is lower than 0.6, but the exact value depends on the specific particle size distribution and other factors, such as the extent of the filter being loaded with previously filtered dust.

Since all parameters of the model [Eq. (4)] are known except for the value of the penetration factor p, it can be determined by using this model for measured indoor and outdoor real-time $PM_{2.5}$ levels. For the measurement in December 2006, the damper position m was being recorded. The model was used several times with m and the measured outdoor $PM_{2.5}$ concentration c_a as the model inputs, and the value of p was being modified with each simulation until the average value of the model-predicted indoor $PM_{2.5}$ concentration c agreed with the measured average indoor concentration. MATLAB® Simulink was used for the simulations with the HVAC model shown in Fig. 3. In this figure, the integration of Eq. (4) is performed by the block in the lower RH corner with the blocks to the left representing either input variables or mathematical operations as defined by the RHS of Eq. (4). Even though the value of m was not being recorded in the July 2005 measurement, it could be calculated based on the HVAC control algorithm and the measured real-time outdoor temperature. The control algorithm is designed for the maximum energy efficiency; the mixing of the fresh air and recirculated air is done in such a ratio that the mixed air temperature is as close as possible to 12.8 °C. It is the supply air temperature required in summer months. If the mixed air temperature is different, it is cooled or heated to that value. The operating range for m is 10–100%. The minimum limit of 10% is based on the minimum fresh air requirements for such a building. The return air temperature is known to be relatively constant around 24 °C, so it was possible to post-calculate the damper position m for the measurement period. Then, the same method as described above for December 2006 was used to determine the filter penetration factor p for the July 2005 measurement.

2.3. $PM_{2.5}$ control algorithm

An HVAC control algorithm was developed that decreases the indoor levels of $PM_{2.5}$. In order to not significantly compromise the purpose of the original control strategy (here energy efficiency), this $PM_{2.5}$ control algorithm is automatically activated only during elevated levels of particles. The value of $5\,\mu g/m^3$ was chosen as the target indoor $PM_{2.5}$ level. If the indoor level exceeds this level, the $PM_{2.5}$ control algorithm is activated. This algorithm is also activated if the outdoor $PM_{2.5}$ level exceeds such a value that has the potential to result in the exceedance of the indoor target level in steady state. The potential is the highest when no air is recirculated, i.e. $m = 1$. In this situation, the following relationship applies to the steady state values:

$$c_{ss} = \frac{pk_v}{k_v + k + k_d} c_{a\text{-}ss}, \tag{5}$$

where c_{ss} is the indoor steady-state $PM_{2.5}$ concentration and c_{a-ss} is the outdoor steady-state concentration. This relationship is used to calculate the outdoor target $PM_{2.5}$ concentration from the indoor target concentration. If the activation of the $PM_{2.5}$ control algorithm were only based on the indoor $PM_{2.5}$ level, then oscillations of the fresh/

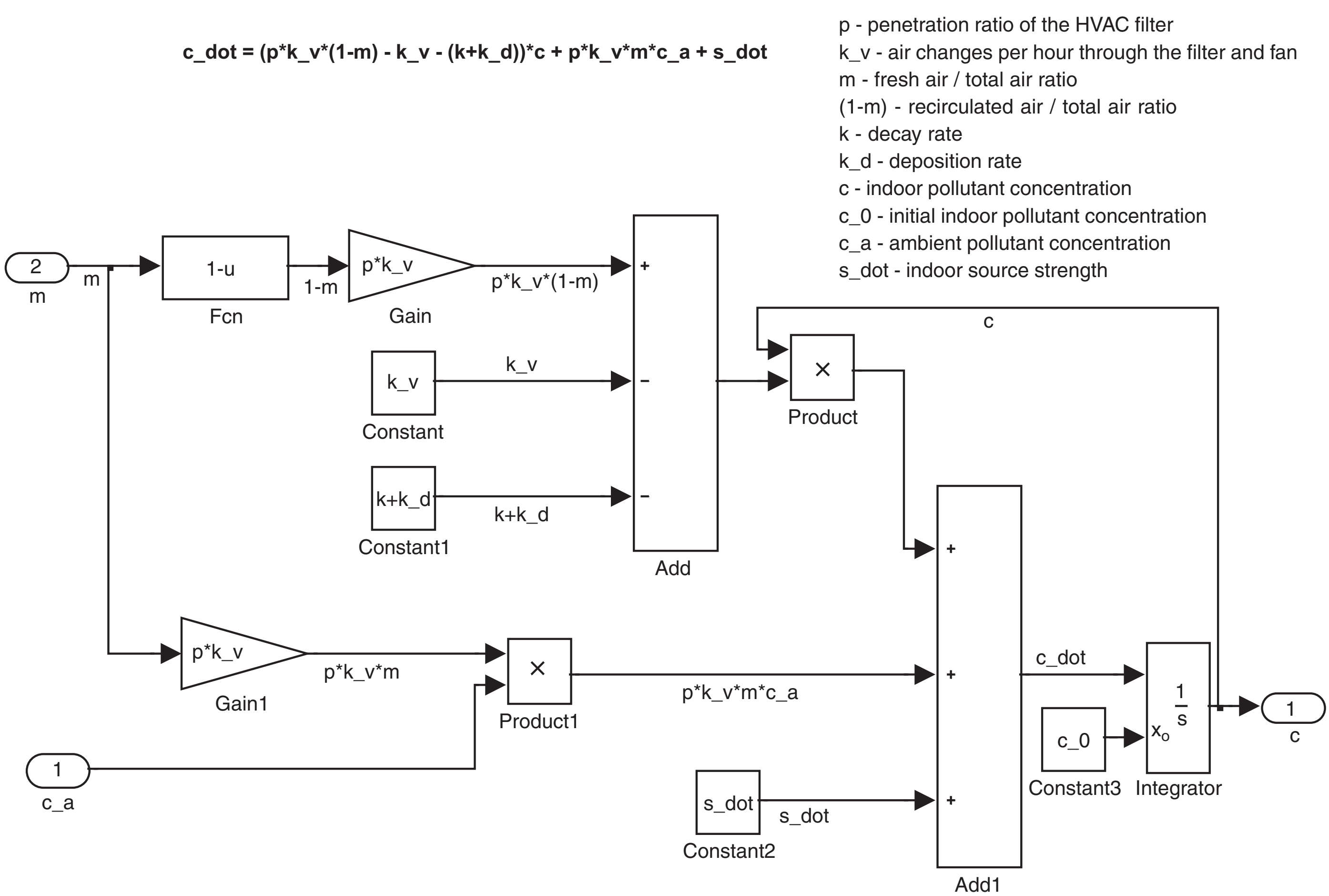

Fig. 3. MATLAB® Simulink model of the HVAC system.

recirculated air damper could result because activating the $PM_{2.5}$ control strategy would lead to decreasing the indoor level underneath the target value, thus deactivating the $PM_{2.5}$ control strategy and increasing the indoor levels again. Similar damper oscillations could result if Eq. (5) for calculating the outdoor target $PM_{2.5}$ concentration was based on the mixing ratio, m, lower than one. With $m<1$, the outdoor target $PM_{2.5}$ concentration would be higher than with $m=1$. This would make it possible for the indoor $PM_{2.5}$ to reach the indoor target concentration in a steady state without the outdoor $PM_{2.5}$ reaching the outdoor target concentration, if m is higher than the value for which the outdoor target $PM_{2.5}$ concentration was calculated. This would result in activating the $PM_{2.5}$ control strategy, which would result in decreasing the indoor $PM_{2.5}$ levels, which would result in deactivating the $PM_{2.5}$ control strategy and increasing the $PM_{2.5}$ levels again. That is why setting the outdoor target $PM_{2.5}$ concentration is based on $m=1$. If the activation of the $PM_{2.5}$ control strategy were only based on the outdoor level, it would not work well for transients when the outdoor level quickly drops but there are still high levels of indoor $PM_{2.5}$; neither would it work for the indoor generated $PM_{2.5}$ (but this would be an unusual situation for an office environment, as mentioned earlier). Therefore, the activation is based on both the outdoor and indoor levels and the condition for activating the $PM_{2.5}$ control strategy can be written as follows:

$$c > c_{\text{target}} \quad \text{or} \quad c_{\text{a}} > c_{\text{a-target}},$$

where c_{target} and $c_{\text{a}-\text{target}}$ are the indoor and outdoor target $PM_{2.5}$ levels, respectively.

The $PM_{2.5}$ control strategy itself is based on the following idea. The cleaner the air entering the HVAC filter, the cleaner air is being supplied into the rooms. The air entering the filter is a mixture of the outdoor air and recirculated air. The $PM_{2.5}$ concentration of the recirculated air is practically the same as the concentration in the rooms. If the indoor $PM_{2.5}$ concentration is higher than the outdoor concentration, the air entering the filter will be cleanest if the recirculated air flow is minimized and the fresh air flow is maximized. The opposite is true if the outdoor $PM_{2.5}$ concentration is higher than the indoor one. Therefore, the setting of the fresh/recirculated air damper position m is determined based on the outdoor and indoor $PM_{2.5}$ concentrations c_{a} and c in the following way:

$$c_{\text{a}} > c \quad \text{then} \quad m = 0.1,$$
$$c_{\text{a}} \leqslant c \quad \text{then} \quad m = 1.0.$$

The value of $m=0.1$ was chosen because it was the minimum value determined during the design of this specific HVAC system in the past based on the minimum ventilation requirements (as mentioned earlier in the description of the original control strategy).

This $PM_{2.5}$ control algorithm was incorporated into the Simulink model (files available from authors on request) and was tested with the outdoor $PM_{2.5}$ data during the smoke episode in July 2005. The indoor $PM_{2.5}$ levels obtained with this control strategy were compared with those original ones obtained with the regular control strategy. The $PM_{2.5}$ control strategy was not tested with the December 2006 data because of very low $PM_{2.5}$ levels; the indoor $PM_{2.5}$ concentration stayed underneath the target value of $5\,\mu g/m^3$ almost all the time. The December 2006 data was only used to verify the HVAC model. For that purpose, it was more suitable than the July 2005 data because of the wide range of changes of the fresh/recirculated air damper position m and because of m being directly recorded.

3. Results

During the December 2006 measurement, the fresh/recirculated air damper position m varied in the range of about 40–95%. The average $PM_{2.5}$ concentration was measured to be $3.8\,\mu g/m^3$ outdoors, and $1.4\,\mu g/m^3$ indoors. The penetration factor of the HVAC filter was found to be 0.47. The real-time outdoor and indoor $PM_{2.5}$ concentrations and the model output are presented in Fig. 4. The model output is almost identical with the measured indoor concentration with the correlation coefficient $r=0.98$.

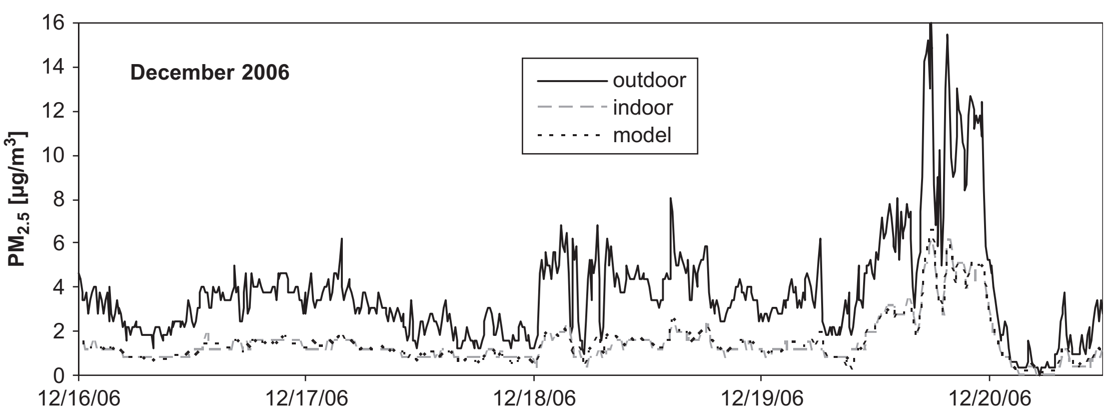

Fig. 4. Measured outdoor and indoor $PM_{2.5}$ concentrations, and the model output in December 2006.

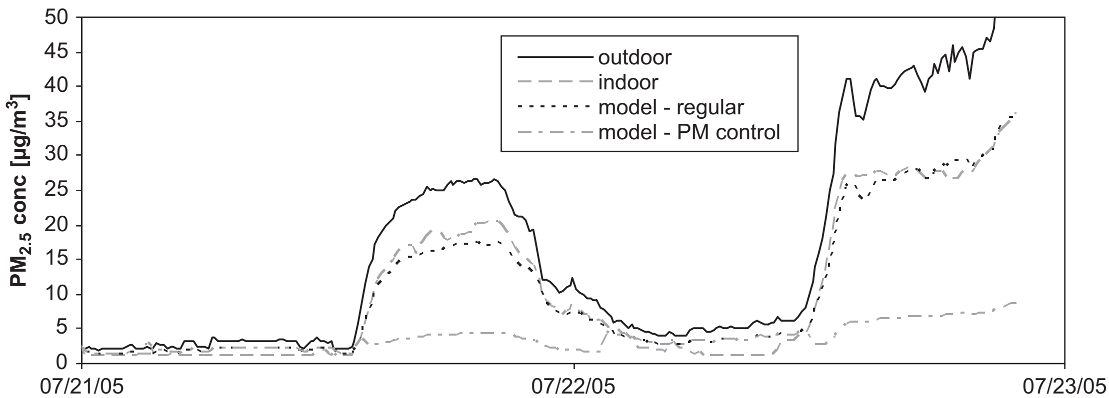

Fig. 5. Measured outdoor and indoor $PM_{2.5}$ concentrations, model output for regular control and model output for $PM_{2.5}$ control in July 2005.

During the July 2005 measurement, the value of m was close to 100% during the whole time, indicating hardly any recirculation of the indoor air. The average outdoor and indoor CO_2 levels were measured to be 373 and 380 ppm, respectively. The average $PM_{2.5}$ concentration was measured to be 16.0 µg/m^3 outdoors and 10.4 µg/m^3 indoors. The penetration factor of the HVAC filter was found to be 0.68. The real-time outdoor and indoor $PM_{2.5}$ concentrations, the model output with regular control, and the model output with $PM_{2.5}$ control are presented in Fig. 5. The average indoor $PM_{2.5}$ concentration with the $PM_{2.5}$ control was 3.6 µg/m^3, i.e. 65% lower than the average indoor concentration with the regular control of 10.4 µg/m^3. The model output with the regular control closely agrees with the measured real-time indoor $PM_{2.5}$ concentration with the correlation coefficient $r = 0.99$.

4. Discussion

The correlation coefficient between the measured indoor concentration and the model-predicted concentration was 0.98 in December 2006 and 0.99 in July 2005. This indicates that the developed model is an accurate tool for predicting the indoor real-time concentration and that the model assumptions were very reasonable, particularly the assumptions that the indoor sources are negligible and that the multi-zone situation of the studied building can be closely approximated with a single-zone situation. It was demonstrated that the developed model can be used to estimate the as-installed HVAC filter penetration factor, a parameter which is otherwise difficult to measure. The as-installed filter penetration factor can be different from that determined in a laboratory test because of possible by-pass flows, specific particle size distribution of the $PM_{2.5}$, or the effect of previously deposited particles on the filter. The penetration factor was found to be 0.47 in December 2006 and 0.68 in July 2005. The value for December 2006 is significantly different from the value for July 2005, even though the same MERV rated filters were used (they were not exactly the same filters, though, because they were replaced between the July 2005 and December 2006 measurements). Moreover, the value of 0.68 is above the maximum of 0.6, which was expected based on the model of a MERV13 filter [12], as explained earlier. Our results initiated an inspection of the filters by the HVAC technicians. It was found that the filters are not sealed and that there is a significant by-pass flow around the filters. Since there were several wild-fire smoke episodes preceding the July 2005 measurement, it is suspected that the HVAC filters were significantly laden with particles. Even though laden filters have normally higher collection efficiency than clean filters, it could have been different with the improperly sealed filters. Clogging the filters could have resulted in a higher by-pass flow and thus a higher proportion of the air not being filtered.

The average outdoor $PM_{2.5}$ level during the December 2006 measurement was only 3.8 µg/m^3. Even though Fairbanks can have high $PM_{2.5}$ levels during the winter, it was shown that this does not necessarily apply to the outskirts of Fairbanks, where the studied building is located. Because of the low levels, the December 2006 data was identified as unsuitable for testing the $PM_{2.5}$ control strategy.

The $PM_{2.5}$ control algorithm was tested using the outdoor $PM_{2.5}$ data from the July 2005 smoke episode. The simulation data showed a significant reduction in the indoor $PM_{2.5}$ levels. The average indoor $PM_{2.5}$ concentration with the $PM_{2.5}$ control was 3.6 µg/m^3, i.e. 65% lower than the average indoor concentration of 10.4 µg/m^3 with the regular control. Even though it represents only the decrease of 6.8 µg/m^3 in this scenario, it should be noted that the difference in the absolute levels would be much higher during more serious episodes. As mentioned earlier, the outdoor $PM_{2.5}$ levels in Fairbanks during wild-fire smoke episodes are known to exceed 1000 µg/m^3; a decrease of 65% in indoor levels in such a situation would have a significant health benefit. The implementation of the $PM_{2.5}$ control strategy presented here would require not only the modification of the current control program, but also installing permanent outdoor and indoor $PM_{2.5}$ sensors. Accurate $PM_{2.5}$ sensors can be very expensive and also very maintenance intensive. For the purpose of this control, though, cheaper and basically maintenance-free laser-photometry based sensors could be used. As mentioned earlier, these sensors have a low absolute accuracy, but that is not crucial for this kind of control strategy, which is mainly based on the comparison of the outdoor and indoor levels.

Although the $PM_{2.5}$ control strategy was shown to have a positive effect on the indoor $PM_{2.5}$ level, it should be mentioned that it can have a negative effect with respect to the purpose of the original strategy. Since the original control strategy was focused on energy efficiency, the energy demand is increased by introducing the $PM_{2.5}$ control strategy. In this specific case, it was calculated that, while the average indoor $PM_{2.5}$ level decreased by 65%, the cooling load increased by 39%. It is because the $PM_{2.5}$ control strategy decreased the outdoor air intake, and the outdoor air temperature during the periods when the $PM_{2.5}$ control strategy was active was generally lower than the indoor temperature. With the original control strategy, the high intake of the outdoor cool air was helping cool the building. Because the intake of the outdoor cool air was lower with the $PM_{2.5}$ control strategy, more energy had to be spent for cooling the indoor air. It should be pointed out, though, that the cooling load is generally small in summers in Alaska, so the increase of 39% does not represent a significant increase in energy consumption. Also, this $PM_{2.5}$ control strategy reduces the particulate concentration of the air passing through the filters, which either prolongs the replacement period of the filters, or reduces the power input of the fans if the replacement intervals are kept the same, thanks to the lower flow resistance of less laden filters. It should also be noted that the $PM_{2.5}$ control strategy can have a negative effect on the levels of pollutants from indoor sources because this control strategy generally decreases the ventilation rate. Elkilani et al. [13] studied residences in Kuwait and found that the indoor levels of volatile organic compounds (VOCs) were always higher than the outdoor levels, which means decreasing the ventilation rate would further increase the indoor VOC levels. Similar things can be said of CO_2 levels. Therefore, the minimum ventilation rate (which is determined by the minimum value of m in here presented $PM_{2.5}$ control strategy) should be based on the dominant indoor pollutant source. Mui and Chan [14] demonstrated how this can be done using radon as an example of the dominant indoor pollutant.

The ideal pollution control strategy would consider the outdoor and indoor levels of all pollutants, the occupancy, and the energy demand and economics of the ventilation settings, and it would find the optimum ventilation setting by finding the one with the minimal total cost. The total cost would include all the external costs associated with breathing the pollutants, such as the cost of treatments, cost associated with reduced productivity, etc. In reality, such a control strategy is impossible because there are hundreds or even thousands of pollutants in the air and we only have a limited information on their impact on health and comfort [15]. However, the control strategy presented in this paper is a viable approach if there is a known dominant pollutant, such as the $PM_{2.5}$ from forest-fire smoke. This strategy could be modified to account for several major pollutants.

5. Conclusions

A Simulink model of an HVAC system was presented in this paper, and it was used to study a control strategy reducing the indoor $PM_{2.5}$ concentrations during episodes of elevated levels. The Simulink model was shown to be a reliable tool for predicting the indoor $PM_{2.5}$ levels at a building in Fairbanks, Alaska based on outdoor levels and variables of the HVAC system. It was also shown to be a useful tool for estimating the HVAC filter efficiency. The results suggest that improperly sealed HVAC filters can have a strongly negative impact on the filtering efficiency. The $PM_{2.5}$ control algorithm introduced in this paper can significantly reduce the indoor $PM_{2.5}$ levels without significantly compromising the purpose of the original control strategy. This $PM_{2.5}$ control strategy was shown to reduce the levels in the studied building by 65%. This can have a significant health benefit during episodes with high levels of $PM_{2.5}$, such as during smoke from near-by wild fires.

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Appendix A. Spplementary Material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.buildenv.2007.11.001.

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