DEVELOPING COMPUTER MODELS TO STUDY THE EFFECT OF OUTDOOR AIR QUALITY ON INDOOR AIR FOR THE PURPOSE OF ENHANCING INDOOR AIR QUALITY

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DEVELOPING COMPUTER MODELS TO STUDY THE EFFECT OF OUTDOOR AIR QUALITY ON INDOOR AIR FOR THE PURPOSE OF ENHANCING INDOOR AIR QUALITY

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Abstract

People in developed countries spend the majority of their time indoors. Therefore, studying the effect of outdoor air quality on indoor air is of a great importance to human health. This thesis presents several dynamic computer models that were developed to study this effect. They estimate indoor pollutant levels based on outdoor levels, ventilation rate, and other factors. Also, an analysis method is presented that allows for quantifying the effect of outdoor air quality on indoor air at a given building based on measured real-time outdoor and indoor pollutant levels. An important part of this method is separating the measured indoor level into two components - a component caused by indoor sources and a component caused by pollutants penetrating from outdoors. This separation is accomplished using a dynamic model, which, unlike some other methods, also allows for processing transient samples and thus simplifies the needed measurements.

Outdoor and indoor pollutant levels were measured at eight buildings in Fairbanks, Alaska and the developed method was used to analyze the data. The main focus was on fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) – the pollutants of major concern in Fairbanks. The effective penetration efficiency for $PM_{2.5}$ ranged from 0.16 to 0.69, and was close to unity for CO. The outdoor generated $PM_{2.5}$ was responsible in average for about 67% of the indoor $PM_{2.5}$ in residences, and close to 100% in office environments. These results imply that reducing outdoor pollution can have significant health benefits even for people spending the majority of their time indoors. An air-quality control algorithm for a Heating, Ventilation, and Air Conditioning (HVAC) system was developed and tested using one of the models. This algorithm was shown to reduce indoor $PM_{2.5}$ levels by 65%. Another model was used to study various ventilation options for a typical Fairbanks home with respect to indoor air quality, energy consumption, overall economy, and environmental impact. Using a Heat Recovery Ventilator (HRV) with an additional filter was shown to be the best option. Another model was successfully used to address key factors for radon mitigation in a home located in a radon-prone area.

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Chapter 1
General Introduction

This thesis presents several computer models that can be used to study the effect of outdoor air quality on indoor air. Analysis methods using these models are also presented. The study described in this thesis demonstrates the use of the developed tools on buildings in Fairbanks, Alaska. The following sections provide basic information regarding indoor and outdoor air quality. Discussions of the pollution in Fairbanks follow. This background information is included before the objective section in order to support the reader's understanding of the thesis goals. At the end of this chapter, the organization of this thesis is explained.

1.1 Indoor Air Quality

People in the United States spend approximately 90% of their time indoors [1], which demonstrates the importance of studying indoor air quality (IAQ). It is affected by many factors including the rate of emissions from indoor sources, ventilation rate, concentration of pollutants in outdoor air, rate of infiltration from soil gases, rate of removal in the indoor environment, and the removal efficiency while entering through a building envelope [2].

Pollutants from indoor sources can be grouped into several categories. Combustion products (from furnaces, stoves, candles, etc.) include carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and particulate matter (PM). Oxides of nitrogen include nitric oxide (NO) and nitrogen dioxide (NO_2). Particulate matter can carry toxic substances, such as polycyclic aromatic hydrocarbons (PAHs). Another category is formed by volatile organic compounds (VOCs), which can be emitted by paints, cleaning compounds, cosmetic products, air fresheners, stored fuels, building materials, and furnishings. VOCs include, for example, benzene, toluene, and formaldehyde. Another category is biological contaminants, which include bacteria, viruses, and molds. Other important indoor pollutants are tobacco smoke and asbestos.

Radon is also usually considered an indoor pollutant, even though it is not generated indoors, unless radon emitting materials are present. Radon is usually generated in the soil underlying a house and infiltrates indoors through the foundation.

While some pollutants can be partly eliminated by proper selection of indoor materials and appliances, in order to address all indoor-generated pollutants, proper ventilation is needed. Proper ventilation, though, is a complicated issue in areas with polluted outdoor air. In such areas, while increased ventilation decreases the levels of indoor-generated pollutants, at the same time, it generally increases the indoor levels of pollutants generated outdoors.

1.2 Outdoor Air Quality

Outdoor pollutants have a direct effect on the quality of air indoors, and therefore, outdoor air quality is an important issue, even though people generally spend much less time outdoors than indoors. Many epidemiological studies [3-5] have shown a strong correlation of mortality and morbidity with outdoor levels of pollutants. Besides the direct effect on human health, pollutants can also have a negative effect on materials, soil, water bodies, and atmosphere. Even though outdoor air pollution is caused by natural sources in certain cases (such as wild fires), most of the air pollution that people are exposed to has a human cause. The beginning of the industrial revolution (18^{th} century), when people started to use fossil fuels to produce mechanical power, can be considered the beginning of anthropogenic outdoor air pollution, even though people had been burning fuels for heating a long time before then. The most significant change occurred in the 20^{th} century with the start of the use of automobiles. Today anthropogenic sources can be grouped into three categories – industry (e.g. steelworks), utilities (e.g. power plants), and personal sources (e.g. automobiles). Emissions from the personal sources in the USA are greater than those from industry and utilities combined [2].

As a result of the Clean Air Act (1963) and its amendments (1970, 1990), the US Environmental Protection Agency (US EPA) sets National Ambient Air Quality

Standards (NAAQS) for six principal pollutants, which are referred to as "criteria" pollutants [6]. These are CO, lead (Pb), NO_x, PM, ozone (O_3), and SO_2. With respect to PM, the former NAAQS regulated only PM_{10}, which relates to particles smaller than 10 μm in diameter. But, studies [7] have shown that fine particles have a higher impact on human health than coarse particles because they penetrate deeper into lungs. Fine particles are defined as those with a aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). Therefore, a standard for $PM_{2.5}$ was introduced into the NAAQS. Due to a lack of evidence linking health problems to long-term exposure to coarse particle pollution, the annual PM10 standard was revoked in 2006. The current NAAQS for all criteria pollutants are shown in Table 1.1. Despite the growing population in the United States, the total emissions of all criteria pollutants are decreasing, except for NO_x emissions which are approximately constant [8].

Table 1.1 National Ambient Air Quality Standards. Source: [6]

Pollutant	**Averaging time**	**Concentration**
CO	8-hour	9 ppm
	1-hour	35 ppm
Pb	Quarterly	1.5 ug/m^3
NO_x	Annual	0.053 ppm
PM_{10}	24-hour	150 ug/m^3
$PM_{2.5}$	Annual	15 ug/m^3
	24-hour	35 ug/m^3
O_3	8-hour	0.08 ppm
	1-hour	0.12 ppm
SO_2	Annual	0.03 ppm
	24-hour	0.14 ppm

Pollutants can be grouped into 2 categories depending on their origin – primary and secondary pollutants. Primary pollutants are those emitted directly, such as CO.

Secondary pollutants are those arising from other pollutants via a chemical reaction in the atmosphere. For example, O_3 is considered a secondary pollutant because, near the earth's surface, it is normally produced from photochemical reactions involving NO_2 and hydrocarbons (HCs).

1.3 Pollution in Fairbanks, Alaska

The Fairbanks North Star Borough (FNSB) is located in interior Alaska and has the population of about 90,000 people. In the wintertime, because of its northern location and thus insufficient solar radiation, it experiences strong ground-based temperature inversions [9]. Pollutants released into the air stay trapped underneath the inversion layer because the inversion (warmer air above colder air) prevents a vertical motion. As a result, pollutants accumulate close to the ground and their concentrations can reach high levels [10]. The general concept of inversion and pollutant accumulation is shown in Figure 1.1. In the wintertime, not only are the atmospheric conditions suitable for trapping pollutants, but also the emissions are higher, mainly because of cold engine

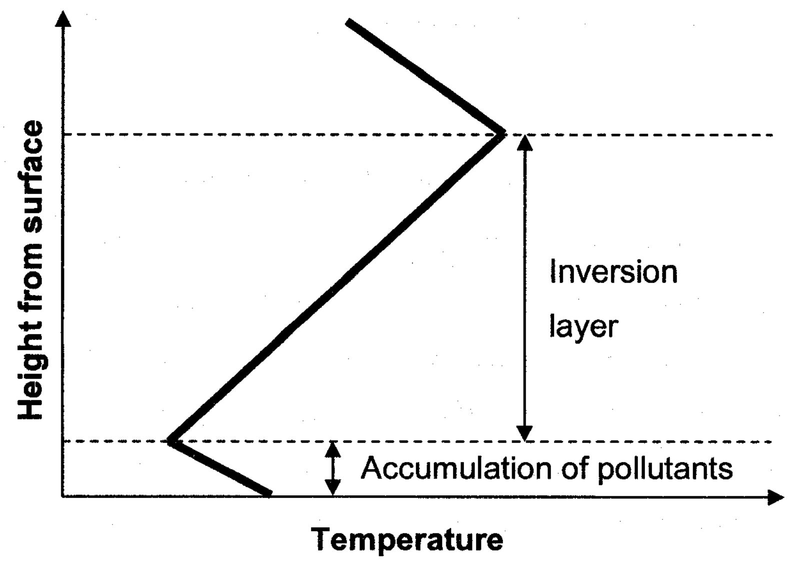

Figure 1.1 General temperature profile with an inversion layer

starts and the operation of heating appliances. The main pollutants of concern are CO and $PM_{2.5}$.

Fairbanks was first identified as having high levels of CO in the early 1970s. Since then, extensive CO monitoring has been performed. The concentrations have continued to exceed the NAAQS for CO until the late 1990s. On March 30, 1998, the urban portion of the borough was designated as a "serious" CO non-attainment area for failing to attain the ambient standard by a given deadline. About 70% of the total 1998 CO emissions in Fairbanks was caused by automobiles [10]. The historical trend in the ambient CO concentration in Fairbanks is shown in Figure 1.2. Even though the current CO levels are still elevated, there hasn't been any violation of the NAAQS for CO since 2000, thanks to improved vehicle technology, implementing various control measures including an I/M program, educating the public, and the support of public transportation.

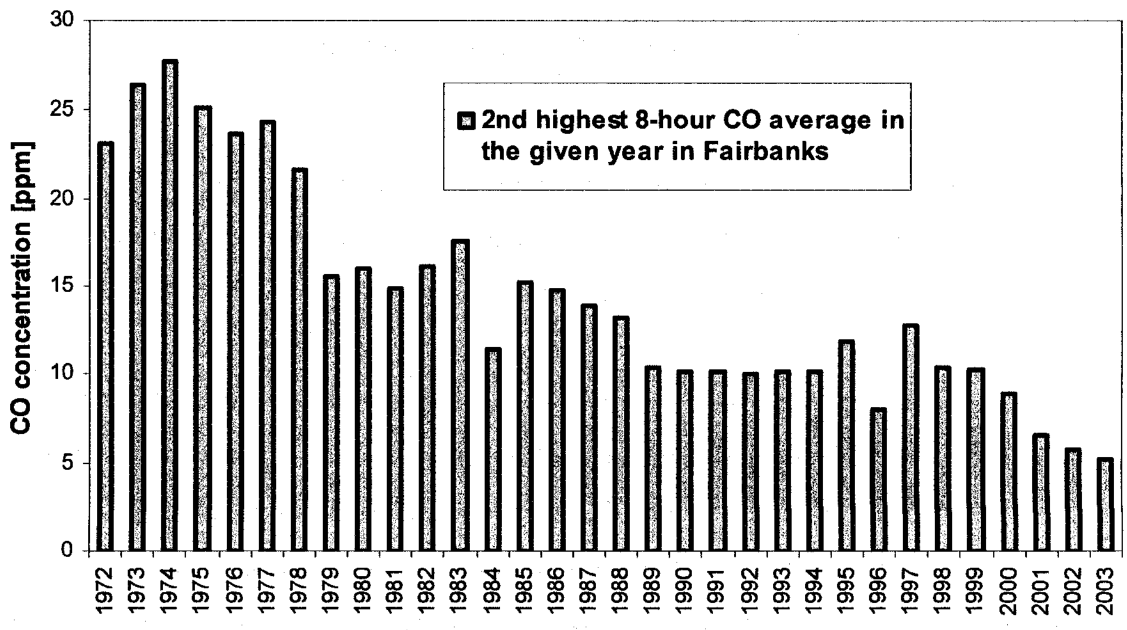

Figure 1.2 Trend in ambient CO concentration in Fairbanks 1972-2003 (data provided by FNSB)

Even though Fairbanks in the wintertime has elevated levels of $PM_{2.5}$, it has not been in violation of the NAAQS. However, in September 2006, the US EPA decreased the

24-hour $PM_{2.5}$ standard from 65 to 35 ug/m^3. This limit was exceeded many times during the winter of 2006-2007 (see Figure 1.3). The US EPA regulations related to this standard are formulated as [6]: "To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 μg/m^3 (effective December 17, 2006)." Based on this regulation, Fairbanks might be in violation of this standard in the future. Even though woodstoves and automobiles are suspected to be the major sources of the wintertime $PM_{2.5}$ in Fairbanks, tremendous uncertainties exist in these estimates, and determining the sources more accurately is the subject of current research.

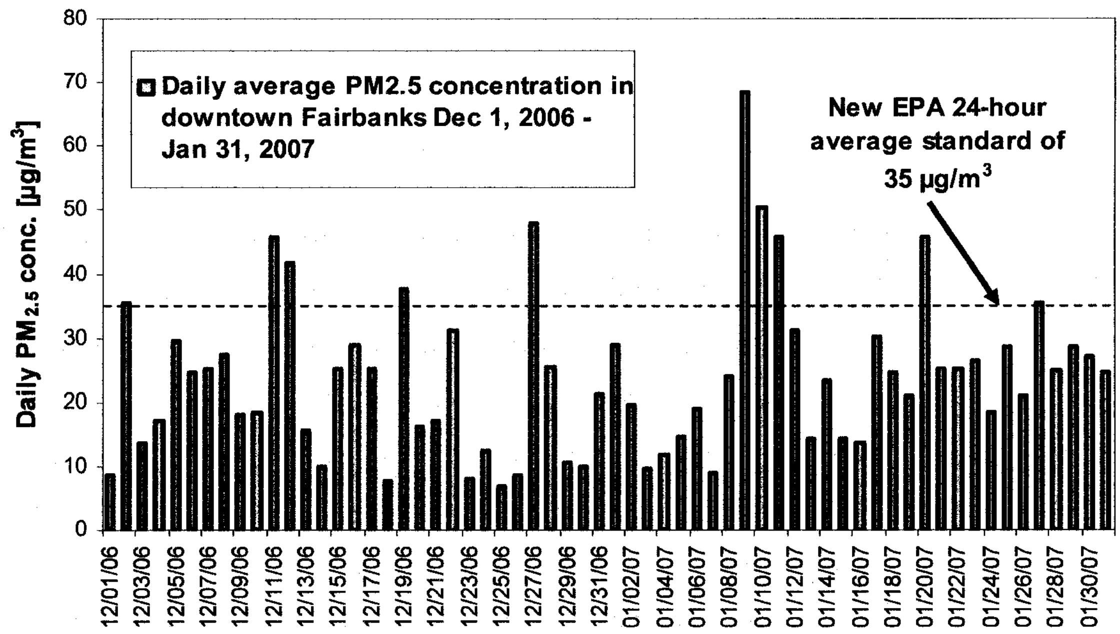

Figure 1.3 $PM_{2.5}$ concentration in downtown Fairbanks Dec 1, 2006 - Jan 31, 2007 with shown exceedances of the new EPA standard (based on preliminary data from FNSB)

Fairbanks can also have elevated levels of $PM_{2.5}$ in the summertime due to the smoke from numerous forest fires in Alaska. This has been a problem especially in recent years and might be associated with global warming. The summer levels of $PM_{2.5}$ in Fairbanks are known to exceed 1000 ug/m^3. Even though the pollution from natural sources is not counted for determining the compliance with the NAAQS, the elevated levels still pose a hazard to human health, and human protection in such situations is an important part of current research.

Radon is another pollutant of natural origin that poses a health risk to a certain population of the FNSB. It is a radioactive gas. Hilly areas around Fairbanks are known to have elevated soil radon concentrations. Even in these areas, the concentrations in the ambient air are very low, but they can be much higher inside buildings because of a stack-effect induced draft from the underlying soil. This is a problem mainly in the wintertime because of a big temperature difference between indoors and outdoors. The US EPA limit for the annual average indoor radon concentration is 4 pCi/L (pico-Curie per liter). One pCi corresponds to 2.2 disintegrations per minute. About 30% of homes in the hills around Fairbanks are estimated to exceed this limit [11]. Radon mitigation systems were shown to be an efficient solution in most of the cases and ongoing research further increases their efficiency.

Since carbon monoxide, fine particulate matter, and radon are the main pollutants of concern in Fairbanks, they will be further elaborated on in the following chapters.

1.4 Carbon Monoxide

Carbon monoxide is a product of incomplete combustion. In an ideal combustion process, carbon (C) combines with oxygen (O_2) and forms CO_2. If the oxygen present during combustion is insufficient, CO is formed instead of CO_2. The major sources of CO are gasoline-fueled vehicles. On- and off-road mobile sources accounted for approximately 80% of the 1997 nationwide emissions inventory for CO [12].

CO is a colorless, odorless gas that is toxic at high concentrations. It readily binds with hemoglobin, which is the substance in the red blood cells that is responsible for the distribution of oxygen. Its affinity with hemoglobin is about 200 times higher than the affinity of oxygen. Consequently, inhaling CO results in a decreased distribution of oxygen in the body. High concentrations of CO can result in headaches, reduced ability to think, and possibly loss of consciousness and death. It has not been determined if there are effects of low-level exposure on healthy individuals. It has been shown, though, that even relatively low CO concentrations can have a negative effect on people with respiratory or cardiovascular diseases [8,12].

1.5 Fine Particulate Matter

Particulates can be solids or liquids, and they can have various size and composition. The main source of $PM_{2.5}$ is combustion. Mechanical actions produce mainly coarse particles with only a very small fraction falling into the fine-particle size region. Fine particles from combustion are formed by two major processes. The first one is condensation of materials vaporized during combustion. These include heavy metals, organic carbon and elemental carbon (pure amorphous carbon, "soot"). The second one is an atmospheric reaction of sulfur oxides and nitrogen oxides initially released as gasses. This results in particles as secondary pollutants – sulfates and nitrates. Important sources of anthropogenic $PM_{2.5}$ include coal burning, wood burning, and diesel engines. Major natural sources of $PM_{2.5}$ include forest fires and volcano eruptions. Particles of anthropogenic origin tend to have more serious consequences on human health than those from natural sources because the anthropogenic particles are usually emitted in areas with high population density.

Inhaling particle-laden air has a negative effect on human health. Various mechanisms in a human respiratory system exist that prevent particles from entering lungs, such as filtering in the nose and trapping particles on mucous membranes of the airways. However, these mechanisms affect mainly coarse particles. Fine particles can penetrate more easily into the lungs, and therefore, pose a higher threat to human health than coarse particles. The particles are then either deposited in the lungs or penetrate into the bloodstream. Therefore, the health effects of $PM_{2.5}$ include both respiratory and cardiovascular diseases. The main health problems linked with the particulate pollution include irritation of the airways, coughing, difficulty breathing, decreased lung function, aggravated asthma, development of chronic bronchitis, irregular heartbeat, nonfatal heart attack, and premature death in people with heart or lung disease [13].

Besides the effect on human health, particulates can also have a negative effect on the environment. One of the effects is a reduced visibility due to their ability to scatter and absorb sunlight. This can be a problem in cities, but also in other areas where visibility is important, such as national parks. Other impacts include settling on ground or water and affecting the nutrient balance of soil or the acidity of water bodies. Particulate pollution can also cause aesthetic damage to important cultural objects, such as statutes and monuments [13].

1.6 Radon

Radon is a naturally occurring, colorless, odorless, and radioactive gas. It can be found in pores in the soil at concentrations sometimes exceeding 1000 pCi/L [14]. The concentrations in the ambient air are very low (typically less than 1 pCi/L), and therefore, do not pose any significant risk to human health. However, concentrations in the indoor air can be much higher than the outdoor concentrations because of a possible draft from the underlying soil. Such a draft can be caused by the stack effect induced by the temperature difference between outdoors and indoors. The USEPA recommended maximum annual average indoor level is 4 pCi/l. Common radon mitigation methods include ventilation, sealing cracks and openings in the house foundation, and subslab suction.

Radon is a product of the decay series of uranium-238. The most stable isotope is radon-222, which has a half-life of 3.8 days. The decay chain results in the emission of alpha particles. The main problem is not radon itself but its daughter products (lead, polonium, and bismuth), which have half-lives of less than 30 minutes. While radon is essentially chemically inert, its daughter products are chemically active and some of them get trapped permanently in the airways. Radon daughter products can also emit beta particles, but alpha particles in this case cause damage because of their low penetration and thus strong local effect. Alpha particles can cause changes to cellular DNA, which can result in cancerous growth.

Radon is the second leading cause of lung cancer in the United States and claims more than 20,000 lives annually [15]. The leading cause is smoking, which claims about 160,000 lives every year. Radon poses a greatly increased risk to smokers because radon daughter products fix themselves on the micro-particles in tobacco smoke.

1.7 Purpose and Objectives of this Thesis

The indoor level of a pollutant is a complex relationship of the ventilation parameters, concentration of the pollutant in the outdoor air, strengths of indoor sources and sinks, concentration of the pollutant in the underlying soil, parameters of the building envelope and the underlying soil, and the driving forces between the ambient and indoor air. Ambient includes both above ground and below ground. The indoor pollutant concentration has two basic components – concentration caused by indoor sources and concentration caused by the penetration of the pollutant from outdoors.

The main objective of this thesis is to develop computer models that can be used to estimate indoor pollutant levels at various ventilation scenarios based on the outdoor levels and other variables. An analysis method was developed to identify the model parameters based on measured real-time indoor and outdoor pollutant levels, and to quantify the effect of outdoor air quality on indoor air. Another objective is to use the developed tools to study the indoor air quality in Fairbanks, Alaska. Measurements of the real-time indoor and outdoor pollutant concentrations were performed at several buildings, including both commercial and residential, and the model identification method was used to determine the model parameters. The measured indoor levels were analyzed in terms of the two basic components (from indoor and outdoor sources). The models were used to estimate the indoor pollutant levels for various building types in Fairbanks at various ventilation scenarios. The energy and economical considerations of the ventilation scenarios were also evaluated. The study was focused on carbon monoxide, fine particulate matter, and radon.

The purpose of this thesis is to provide tools that can be used to find ways to enhance indoor air quality in an energy- and economically-efficient manner, to use these tools for buildings in Fairbanks, and to suggest specific solutions. The ultimate purpose is to contribute to the enhancement of public health.

1.8 Organization of this Thesis

This thesis is written in the manuscript format. The four main chapters (Chapters 3-6) are papers that were submitted to various journals. In addition to these chapters, this thesis has an introductory chapter (Chapter 1), a chapter describing measurement methods including the test matrix (Chapter 2), a chapter (Chapter 7) with general results and discussion, a conclusions chapter (Chapter 8), and an appendix. Chapter 2 on measurement methods was included for completeness because the papers submitted to journals deal mainly with the analysis methods and results rather than measurement methods. Chapter 2 includes the description of the instruments used to measure the indoor and outdoor pollutant levels, measurement procedures, and the summaries of the measurements performed at each individual building. The focus of the main chapters (Chapters 3-6) is briefly discussed in the following paragraphs:

Chapter 3 is a paper titled "Use of a State-Space Model to Study the Effect of Outdoor Air Quality on Indoor Air in Fairbanks Alaska" that was submitted to the Indoor and Built Environment journal. It describes a state-space model that can estimate the component of the indoor pollutant level caused by outdoor sources based on the real-time outdoor pollutant concentration. It also describes an analysis method to estimate the model parameters based on the measured real-time indoor and outdoor pollutant concentrations. Its use is demonstrated on CO and $PM_{2.5}$ at buildings in Fairbanks. The model parameter estimates for $PM_{2.5}$ form the basis for model parameters in the following chapters. This analysis method is also used to quantify the overall effect of outdoor CO and $PM_{2.5}$ levels on the indoor air and to determine the proportions of the two basic components (from indoor and outdoor sources) of the indoor $PM_{2.5}$ for the buildings studied in Fairbanks.

Chapter 4 is a paper titled "Simulink® HVAC Air-Quality Model and its Use to Test a $PM_{2.5}$ Control Strategy" that was submitted to the Building and Environment journal. It describes a MATLAB® Simulink® model of a commercial building in Fairbanks equipped with a Heating, Ventilation, and Air Conditioning (HVAC) system. This model can estimate the indoor pollutant levels based on the real-time outdoor levels. This paper also describes an HVAC control algorithm that reduces the indoor $PM_{2.5}$ levels. This control algorithm was tested using the Simulink® model and the benefits of using this $PM_{2.5}$ control over the regular control were evaluated.

Chapter 5 is a paper titled "Use of Simulink® to Evaluate the Air Quality and Energy Performance of HRV-Equipped Residences in Fairbanks, Alaska" that was submitted to the Energy and Buildings journal. It presents a MATLAB® Simulink® model of a building equipped with a Heat Recovery Ventilator (HRV). This model can estimate the indoor pollutant levels in such a building and the energy consumption associated with ventilation. This model was used to evaluate various ventilation scenarios for a typical home in Fairbanks in terms of indoor $PM_{2.5}$ levels and energy consumption. Three main scenarios were compared – a naturally ventilated home, a home ventilated with an HRV, and a home ventilated with an HRV and additional particulate filters.

Chapter 6 is a paper titled "Use of Simulink® to Address Key Factors for Radon Mitigation in a Fairbanks Home" that was submitted to the Health Physics journal. It presents a MATLAB® Simulink® model that can estimate indoor radon levels based on variables associated with various radon mitigation strategies. The factors considered in the model are the ventilation rate, the flow resistance of the house foundation, and the differential pressure between the subslab and house interior.

Even though the main results are presented and discussed in the individual papers, additional results exist that were not included in the papers due to space limitations, but are worth presenting in this thesis. These results are presented and discussed in Chapter 7 "General Results and Discussion." Chapter 8 "General Conclusions" summarizes all conclusions of this thesis.

The appendix of the thesis presents an extended set of results (in the form of tables and graphs) from the state-space model analysis method described in Chapter 3. The results included in the paper were limited because of space considerations. The data in the appendix is referred to in the "General Results and Discussion" chapter. A block diagram showing the individual stages of the whole research and how they relate to the chapters of this thesis is shown in Figure 1.4.

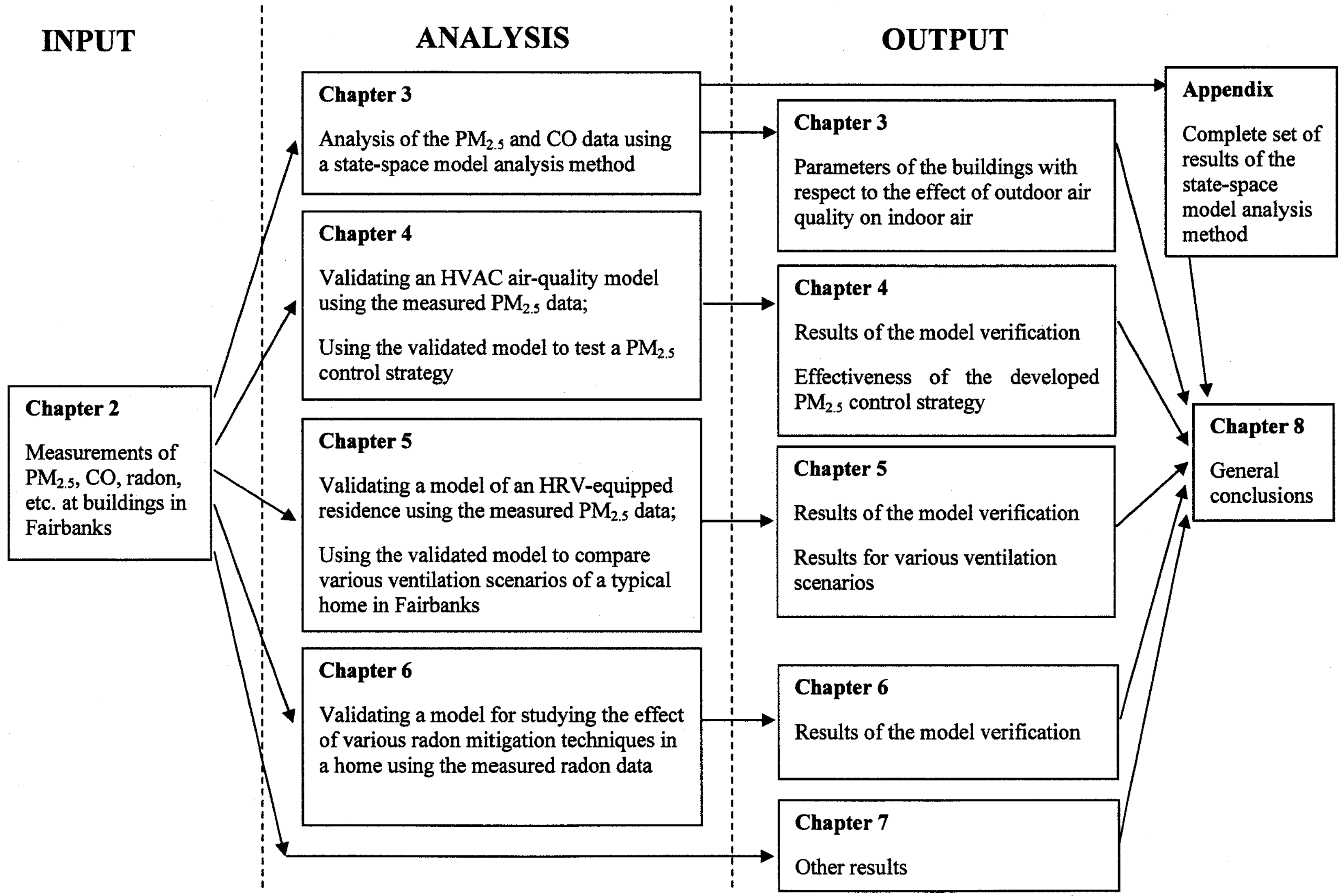

Figure 1.4 Flow chart of the research with references to individual chapters

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Chapter 2
Measurement Methods

2.1 Instruments

The following is a description of all instruments used in this study to measure the indoor and outdoor levels of pollutants and other variables. The main instruments are shown in Figure 2.1. The outdoor instruments were placed in an environmental enclosure with a heater and a thermostat (set to 21 °C) in order to prevent calibration drift due to temperature fluctuations and maintain a proper operating temperature. The outdoor air was brought to the instruments via flexible vinyl tubing.

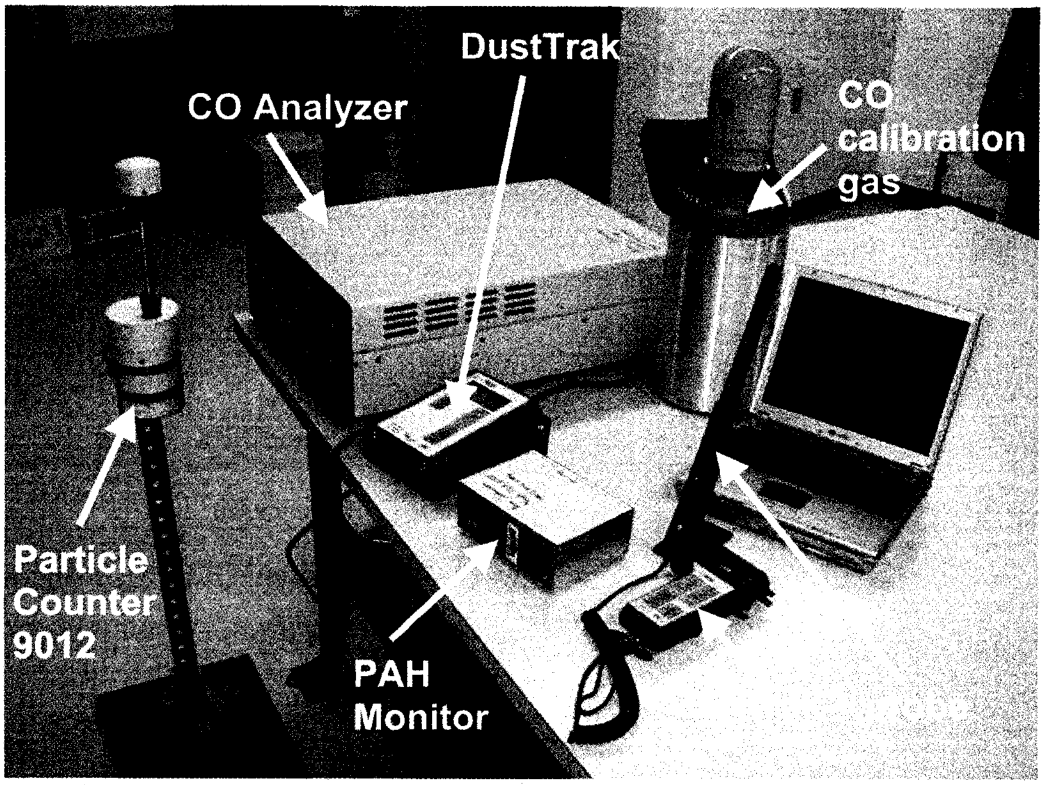

Figure 2.1 Main air-quality instruments (photo by T. Marsik)

2.1.1 CO Analyzer

The API 300E Gas Filter Correlation CO Analyzer is an instrument for accurate real-time monitoring of CO concentrations. It calculates the CO concentration from the attenuation of infrared radiation (IR) at a certain wavelength (4.7 μm). The folded path of the infrared beam that passes through the sample chamber is 14 meters. The fundamentals of the measurement principle are shown in Figure 2.2.

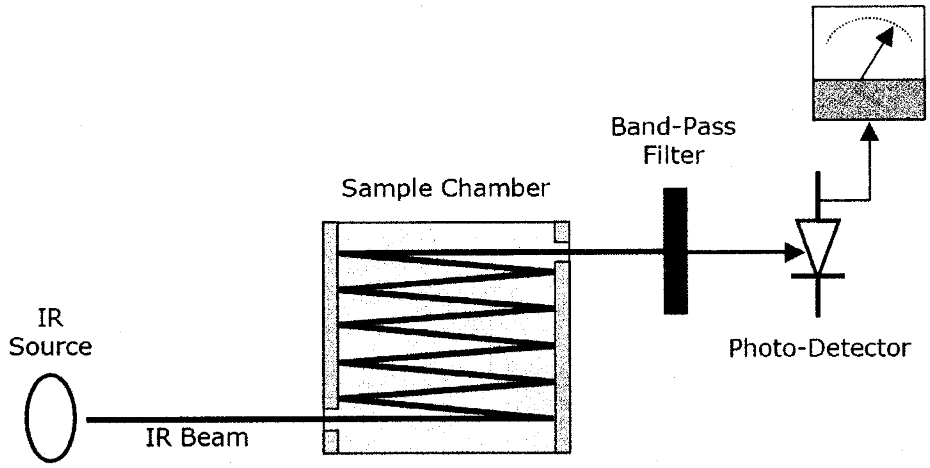

Figure 2.2 CO Analyzer measurement fundamentals (source: [1])

During deployments, the CO Analyzer was calibrated about once a week. Zero calibration was done using a zero gas, which was obtained using the instrument's internal CO scrubber. Span calibration was done using a span gas of known CO concentration (8.77 ppm) which was supplied from a pressurized cylinder. The logging interval was set to 10 min, and the data was stored in the instrument's internal memory.

Where physically possible, the CO Analyzer was used to measure both indoor and outdoor CO by switching an internal valve between two input ports in one-hour cycles (20 minutes for indoor measurement and 40 minutes for outdoor measurement). The CO Analyzer was placed indoors and the outdoor air was brought to one of the input ports via Teflon tubing.

2.1.2 Q-Trak

A TSI 8551 Q-Trak is an instrument for real-time measurements of CO, CO_2, temperature (T), and relative humidity (RH). The Q-Trak uses an electro-chemical sensor for the measurement of CO, infrared sensor for CO_2, a thermistor for T, and a thin-film capacitor for RH. Because of the low accuracy of the CO sensor (±3 ppm), the CO data was not used in most of the measurements. It was only used where relatively high CO concentrations were measured (garages). The CO_2 data was used to estimate the ventilation rates of the measured buildings. This was done by evaluating the CO_2 decay rate after everyone left the building [2]. The CO_2 data was also helpful to estimate the building use patterns. The T and RH data was useful to verify the operating conditions for the instruments. For example, high RH can result in incorrect $PM_{2.5}$ measurements because of the condensation of water on the particles.

The logging interval was usually set to 2 minutes for convenience, and the data was stored in the internal memory. For the data analysis, the collected data was usually converted into 10-min average samples. The CO_2 sensor was usually calibrated before deployments using a zero calibration gas (pure nitrogen), and a span calibration gas with a CO_2 concentration of 1000 ppm. If the CO data was going to be used, the CO sensor was calibrated before deployments using the zero air from the 300E CO Analyzer's internal scrubber and the 8.77 ppm CO from the pressurized cylinder as a span gas.

2.1.3 Toxi Ultra

The Biosystems Toxi Ultra with an electrochemical CO sensor was used for CO monitoring in an unheated garage, where the Q-Trak couldn't be used because of an insufficient temperature operating range. The logging interval was set to 3 min 20 sec, and the data was stored in the internal memory. For the data analysis, the collected data was converted into 10-min average samples.

2.1.4 DustTrak

A TSI 8520 DustTrak (see Figure 2.3) is an instrument for real-time PM measurements. It uses an inertial impactor in order to separate the particle-size fraction needed for the measurements. In our case, a $PM_{2.5}$ impactor was used. The particle-laden air is drawn into an optical chamber where it is exposed to a laser beam. The light is scattered by the particles in the air, and the intensity of the scattered light is detected and used to calculate the $PM_{2.5}$ concentration. The advantage of this method is that it provides real-time data, but the disadvantage is that the data is not very accurate. The accuracy is low because the intensity of the scattered light depends on other properties than just the mass concentration. These properties include the reflective properties of the particles and the particle-size distribution. The accuracy can be increased, though, if a correction factor is

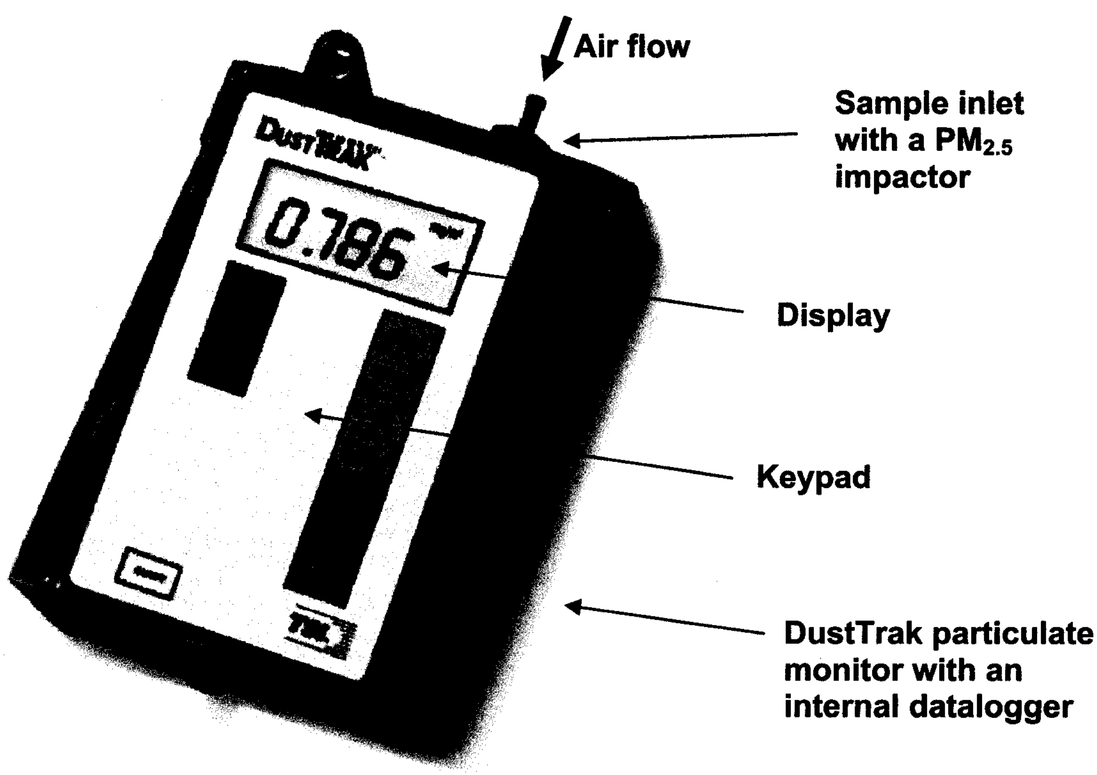

Figure 2.3 DustTrak particulate monitor (photo – source: [3])

applied to the measured data. This correction factor can be determined if another instrument (collocated with the DustTrak) is used that measures accurately the long-term average $PM_{2.5}$ concentration. The average DustTrak correction factor was 0.41 for indoor and 0.49 for outdoor $PM_{2.5}$. These values were used for measurements for which the accurate long-term average level was not available.

The logging interval was usually set to 2 minutes, and the data was stored in the internal memory. For the data analysis, the collected data was usually converted into 10-min average samples. During deployments, a zero calibration was performed in the intervals of about 1 week using a High Efficiency Particulate Air (HEPA) filter. At the same time, a flow calibration was performed using a flowmeter, and the $PM_{2.5}$ impactor was cleaned.

2.1.5 Micro-Environmental Monitor

The MSP 400 Micro-Environmental Monitor (MEM) is an instrument that collects particulate matter on a filter paper. A $PM_{2.5}$ impactor was used to collect $PM_{2.5}$. The air was drawn through the filter paper at 10 L/min. 0.8-μm polycarbonate filter paper was used for the $PM_{2.5}$ collection, and it was replaced about once per week. Each filter paper was weighed before and after the collection and the mass difference was used to evaluate the average $PM_{2.5}$ concentration.

2.1.6 Personal Environmental Monitor

The SKC 761-203A Personal Environmental Monitor (PEM) with the SKC 224-PCXR4 pump is a setup that allows collecting $PM_{2.5}$ on filter paper. It was used in a similar way as the MEM except that the flow rate was 4 L/min. The PEM was usually used for outdoor measurements, while the MEM was used for indoor measurements.

2.1.7 E-BAM

The Met One E-BAM is an instrument for PM measurements. A $PM_{2.5}$ sharp cut cyclone is included to measure $PM_{2.5}$. The E-BAM draws the particle-laden air through a filter tape and measures the collected mass via the attenuation of beta radiation. The measured $PM_{2.5}$ concentration is recorded in the internal memory at user-selectable intervals. This principle allows for near-real-time $PM_{2.5}$ monitoring. However, the accuracy depends on the amount of mass collected throughout the averaging interval, and therefore, more accurate values are obtained for longer averaging intervals. The accuracy for 24-hour averages is claimed to be 2.5 ug/m3. For this reason, the E-BAM was used for long-term averages rather than real-time monitoring.

The E-BAM calibration and maintenance was done based on the schedule recommended by the manufacturer. This included a leak check, calibration of external temperature and pressure sensors, flow calibration, check for ending tape, water jar check, pump test, nozzle/vane area check, inlet and sharp cut cyclone cleaning, filter T and RH sensor check, and zero and span verification.

2.1.8 BAM-1020

The Met One BAM-1020 is a beta attenuation PM monitor operating on a similar principle as the E-BAM. The BAM-1020 was designed for stationary applications, while the E-BAM is a portable instrument. The BAM-1020 is located at a permanent monitoring station in downtown Fairbanks and operated by the FNSB air quality division who shares their data with us.

2.1.9 Particle Counter 237B

The Met One 237B Particle Counter measures the concentration of particles in 6 size ranges (0.3, 0.5, 0.7, 1.0, 2.0, and 5.0 μm). The particle laden air is drawn through a laser based optical sensor. Using the light scattered by the particles, they are sized and counted. This Particle Counter also has an external T and RH sensor. The logging interval was usually set to 20 minutes because of the limited capacity of the internal memory. For the analysis, the data was converted into 10-min average data using linear interpolation.

2.1.10 Particle Counter 9012

The Met One 9012 Particle Counter measures the concentration of particles in 6 size ranges (0.3, 0.5, 0.7, 1.0, 2.5, and 10.0 μm). It operates on a similar principle as the Particle Counter 237B. It doesn't have an internal memory. The data was transmitted via an RS232 serial cable to a laptop where the data was stored. The logging interval was set to 1 minute, and, for the data analysis, the collected data was converted into 10-min average samples. The Particle Counter 9012 was usually used for indoor measurements, while the Particle Counter 237B was usually placed in an outdoor environmental enclosure.

2.1.11 PAH Monitor

An EcoChem PAS 2000 CE is an instrument for real-time monitoring of PAH (polycyclic aromatic hydrocarbons) concentrations. It uses an ultra-violet (UV) lamp with a narrow band to ionize the PAH coated aerosol. The charge is then measured using an electric field and the PAH concentration is evaluated. The logging interval was set to 2 minutes, and the data was stored in the internal memory. For the data analysis, the collected data was usually converted into 10-min average samples.

2.1.12 Aethalometer

The Magee Scientific AE-21 Aethalometer is an instrument for real-time monitoring of the concentration of elemental carbon (also referred to as soot or black carbon). It continuously draws in the measured air and collects the aerosol on a quartz fiber filter tape. The collected mass is evaluated via an optical analysis. The absorption of the wavelength of 880 nm is used for the elemental carbon and the difference between the above absorption and absorption of UV light (370 nm) for other components. The logging interval was usually set to 5 minutes, and the data was stored in the internal memory. For the data analysis, the collected data was usually converted into 10-min average samples. Unlike most of the other instruments, the Aethalometer was only used at a central location (UAF Energy Center) because of difficulties with its transportation.

2.1.13 T Sensor with HOBO Datalogger

The TMC6-HA thermistor (accuracy of ±0.5 °C) with an Onset HOBO H08-002-02 datalogger was used to measure the outdoor temperature. The sensor was used because of its suitable temperature operating range that reaches down to -40 °C. The logging interval was normally set to 2 minutes, and for the data analysis, the collected data was usually converted into 10-min average samples.

2.1.14 VOC Monitor

The RAE PGM-7240 PPB VOC Monitor is an instrument for monitoring total volatile organic compounds (TVOCs). It uses a photo-ionization detector (PID). As organic vapors pass by a UV lamp in an ionization chamber, they are photo-ionized and the ejected electrons are detected as current. The TVOC concentration is then evaluated based on the current. This VOC Monitor does not differentiate between individual volatile organic compounds. Isobutylene was set as the reference gas. The resulting concentration of the TVOCs corresponds to the concentration of isobutylene that would result in the same photo-ionization effect. Even though the VOC Monitor allows for real-time monitoring and data storage in the internal memory, performing this was beyond the scope of our study. In our study, the VOC Monitor was only used for one-time samples at various locations inside the studied buildings ("walk-through").

2.1.15 Differential Pressure Transducer with HOBO Datalogger

An OMEGA PX274 Differential Pressure Transducer with an Onset HOBO H08-002-02 Datalogger was used to measure the differential pressure between the subslab and basement and also the differential pressure between outdoors and indoors during certain radon measurements. The logging interval was normally set to 2 minutes, and for the data analysis, the collected data was usually converted into 10-min average samples.

2.1.16 Continuous Radon Monitor

A Sun Nuclear 1027 Continuous Radon Monitor (CRM) is an instrument for near-real-time monitoring of radon concentrations. It has a photodiode sensor that detects alpha particles. The logging interval was usually set to 24 hours and the data was stored in the internal memory. In come cases, a shorter logging interval (e.g. 4 hours) was used in order to better study transient radon concentrations.

2.1.17 Alpha-Track

An RSSI Alpha-Track is a passive detector for evaluating long-term average radon concentrations. Alpha particles make tracks on a film inside the detector. At the end of a deployment, the Alpha-Track is sent to a laboratory where the tracks are counted and the average radon concentration is calculated. In our measurements, the Alpha-Tracks were normally collocated with CRMs. The average deployment period was about two months. Even though Alpha-Tracks don't allow for real-time monitoring, they provide for highly accurate measurements of average radon concentrations. Therefore, they were often used to verify the data obtained using CRMs.

2.1.18 Organic Vapor Diffusion Monitor

A 3M 3510 Organic Vapor Diffusion Monitor is a passive detector for evaluating average concentrations of volatile organic compounds. It contains a charcoal adsorbent pad that, after deployment, is sent to a specialized laboratory for analysis of requested compounds. In our measurements, the analyzed compounds were benzene, n-hexane, and toluene. The deployment period was about a week.

2.1.19 Formaldehyde Diffusion Monitor

A 3M 3720 Formaldehyde Diffusion Monitor is a passive detector for evaluating average formaldehyde concentrations. After deployment, it is sent to a specialized laboratory for analysis. The average deployment period was about 10 hours.

2.2 Test Matrix

Measurements of indoor and outdoor pollutant concentrations were performed at three residential houses and five commercial buildings in the Fairbanks area between June 2005 and February 2007. Multiple measurement periods (during different seasons) were used for several of these buildings. During each measurement period, a simultaneous real-time measurement of outdoor and indoor pollutant levels was performed. The measurements at the individual buildings are described in the following sections, starting with residential buildings.

2.2.1 Ellesmere Drive

A new residential building located on Ellesmere Drive at Chena Ridge in Fairbanks, Alaska was selected for our monitoring because of its location, type of building, and also the cooperation of the occupants. This was the only studied building that was outside the area designated as "non-attainment" for CO. The building has an HRV, an attached garage, and it is located in a hilly area known to have elevated soil radon concentrations. The main measurements were performed in two different measurement periods.

The first period was from 6/22/05 to 7/12/05. The instruments deployed in the basement were: CRM, Alpha-Track, Differential Pressure Transducer with HOBO Datalogger, and Formaldehyde Diffusion Monitor. The instruments on the first floor were: Q-Trak, DustTrak, PAH Monitor, CRM, Alpha-Track, and Formaldehyde and Organic Vapor Diffusion Monitors. Another CRM, Alpha-Track, and Formaldehyde Diffusion Monitor were deployed on the second floor. A "walk-through" with the VOC Monitor was performed inside the house. The outdoor instruments were: Q-Trak, DustTrak, T Sensor with HOBO Datalogger, and Aethalometer.

The second period was from 12/30/05 to 1/12/06. The instruments deployed in the basement were: CRM, Alpha-Track, and a differential pressure transducer with a HOBO Datalogger for subslab-basement measurements. The instruments on the first floor were: Q-Trak, DustTrak, E-BAM, PAH Monitor, Particle Counter 9012, CO Analyzer, MEM, CRM, Alpha-Track, and Formaldehyde and Organic Vapor Monitors. Another Q-Trak and Organic Vapor Diffusion Monitor were deployed in the garage. A "walk-through" with the VOC Monitor was performed inside the house. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, and T Sensor with HOBO Datalogger. The E-BAM was move outside from inside in the middle of the measurement period. The Alpha-Tracks were deployed for an extended period, which ended on 2/12/06. Because of the failure of the outdoor DustTrak, only the period from 12/30/05 to 1/6/06 was used for the $PM_{2.5}$ analysis.

Additional radon measurements were performed after an active subslab depressurization (ASD) system was installed. From 2/13/06 to 4/11/06, two CRMs and two Alpha-Tracks were installed, one of each in the basement and one of each on the first floor. From 4/26/06 to 7/14/06, two CRMs were collocated in the basement. From 7/20/06 to 10/11/06, a CRM and an Alpha-Track were installed in the basement, and a CRM, an Alpha-Track, and a Q-Trak were installed on the first floor. For part of the period, the differential pressure between the subslab and indoors, and the differential pressure between outdoors and indoors were measured using differential pressure transducers.

2.2.2 Jack Street

A residential building on Jack Street was selected for our monitoring. It is a naturally ventilated building with an attached garage. It is located in the non-attainment area. The measurements were performed in two different measurement periods.

The first period was from 10/3/05 to 10/17/05. The instruments deployed in the living area were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, and CO Analyzer. Another Q-Trak was deployed in the garage. A "walk-through" with the VOC Monitor was performed inside the house. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, E-BAM, T Sensor with HOBO Datalogger, and an Aethalometer.

The second period was from 2/11/06 to 2/27/06. The instruments deployed in the living area were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, CO Analyzer, MEM, and Formaldehyde Diffusion Monitor. The Toxi Ultra was deployed in the garage. A "walk-through" with the VOC Monitor was performed inside the house. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, E-BAM, T Sensor with HOBO datalogger, and an Aethalometer. The E-BAM was moved inside from the outside in the middle of the deployment. Starting on 2/15/06, the CO Analyzer was set to monitor both indoor and outdoor CO, using an internal valve to switch between two input ports. Because of the failure of the indoor DustTrak, only the period from 2/15/06 to 2/27/06 was used for the analysis.

2.2.3 Hamilton Acres

A residential building in Hamilton Acres was selected for our monitoring. It is a naturally ventilated building with an attached garage. It is located in the non-attainment area.

The deployment period was from 11/16/05 to 11/30/05. The instruments deployed in the living area were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, CO Analyzer, E-BAM, and Organic Vapor Diffusion Monitor. Another Q-Trak was deployed at a different location in the living area in order to check the mixing of the indoor air. Another Q-Trak and Organic Vapor Diffusion Monitor were deployed in the garage. A "walk-through" with the VOC Monitor was performed inside the house. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, T Sensor with HOBO Datalogger, and an Aethalometer.

2.2.4 UAF Duckering

The Duckering building on the UAF campus was the first commercial building selected for our monitoring. It is a building at the boundary of the non-attainment area. Ventilation is provided using an HVAC system with filters of the Minimum Efficiency Reporting Value (MERV) 13. The HVAC system uses a Direct Digital Control (DDC) system, which allows for logging HVAC variables. The outdoor measurements were performed on the roof of the neighboring building (Brooks). The measurements were performed in four different measurement periods.

The first period was from 7/21/05 to 7/23/05. The instruments deployed in an office on the first floor were: Q-Trak, DustTrak, CO Analyzer, and CRM. The instruments deployed in an office on the third floor were: Q-Trak, DustTrak, PAH Monitor, and CRM. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, T sensor with HOBO Datalogger, and an Aethalometer.

The second period was from 3/3/06 to 3/16/06. All indoor instruments were deployed in the office on the first floor. The indoor instruments were: Q-Trak, DustTrak, PAH Monitor, MEM, and E-BAM. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, T Sensor with HOBO Datalogger, and an Aethalometer.

The third period was from 8/23/06 to 9/5/06. The instruments deployed in an office on the first floor were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, MEM, and E-BAM. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, and PEM. The HVAC variables were being logged during this measurement.

The fourth period was from 12/15/06 to 12/20/06. The instruments deployed in an office on the first floor were: DustTrak, MEM, and E-BAM. The outdoor instruments were: DustTrak, and PEM. The HVAC variables were being logged during this measurement.

2.2.5 FNSB Transportation Building

The building housing the FNSB transportation department was selected as the second commercial building for our study. This building is in the non-attainment area. Ventilation is provided using an HVAC system with MERV 8-rated filters. One part of the building has offices and the other part is a garage/workshop for buses.

The deployment period was from 12/9/05 to 12/19/05. The instruments deployed in an office on the second floor were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, E-BAM, CO Analyzer, and Organic Vapor Diffusion Monitor. Another Q-Trak was deployed in the garage/workshop. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, T Sensor with HOBO Datalogger, and Aethalometer.

2.2.6 Courthouse Square

The Courthouse Square building was selected as the third commercial building for our study. It is an office building located in the downtown Fairbanks, therefore, in the middle of the non-attainment area. Ventilation is provided using an HVAC system. All indoor measurements were performed in an office on the second floor. A permanent CO monitor belonging to the FNSB is located on the corner of this building; the data was provided to us to be used as outdoor CO data. Other outdoor measurements were performed in a nearby location on the roof of the State Office building. The BAM 1020 is also located on this roof; the data was provided to us by the FNSB.

The deployment period was from 1/24/06 to 2/7/06 for indoor instruments and from 1/27/06 to 2/8/06 for outdoor instruments. The indoor instruments (deployed in the second floor office) were: Q-Trak, DustTrak, PAH Monitor, MEM, and CO Analyzer. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, and T Sensor with HOBO Datalogger.

2.2.7 UAF Brooks

The Brooks building on the UAF campus was another commercial building selected for our study because it allows for simultaneous monitoring of outdoor and indoor CO with one instrument without modifications to the building envelope. The CO Analyzer was installed on the highest floor of a staircase, next to a roof access door in the building. The outdoor air was brought to the instrument via tubing going through a seal in the door.

This setup allows for accurate evaluation of the relative indoor and outdoor CO levels, because the effect of disturbances (such as zero drift) is, for the most part, canceled. The measurement was performed in two different measurement periods. The first one was from 3/3/06 to 3/16/06, and the second one was from 12/8/06 to 12/22/06.

2.2.8 CCHRC RTF

The Cold Climate Housing Research Center (CCHRC) Research and Testing Facility (RTF) was the last building selected for our study. It is located at the boundary of the non-attainment area, and the ventilation is provided by several HRVs. The indoor measurements were performed in an office that is served by an HRV with MERV 11 filters.

The deployment period was from 1/31/07 to 2/20/07. The indoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 9012, MEM, and E-BAM. The CO Analyzer was deployed at the same indoor location and monitored both indoor and outdoor CO levels. A "walk-through" with the VOC Monitor was performed inside the building. The outdoor instruments were: Q-Trak, DustTrak, PAH Monitor, Particle Counter 237B, PEM, and Aethalometer.

The settings of the HRV are controlled by a SIEMENS control system based on occupancy, and the settings were being recorded during part of the measurement period. Outdoor data from part of the measurement period was lost because of a power failure of the environmental enclosure. The pump of the PEM failed during the remainder of the measurement period, and therefore, no accurate average $PM_{2.5}$ concentration was obtained. The general DustTrak correction factor of 0.49 was used for the outdoor $PM_{2.5}$. Because of the HRV settings and the loss of data, only the period from 2/16/07 to 2/20/07 was used for the $PM_{2.5}$ analysis.

2.3 References

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Chapter 3
Use of a State-Space Model to Study the Effect of Outdoor Air Quality on Indoor Air in Fairbanks, Alaska*

Abstract

A usual method of studying the effective penetration efficiency of pollutants into buildings consists of performing a linear regression of outdoor and indoor samples. But because of the dynamic relationship between outdoor and indoor concentrations, this method requires either long-term averages or steady-state conditions. Other methods use dynamic models, but these normally require the knowledge of model parameters, such as the ventilation rate. This paper presents a state-space model analysis method that can be used for transient samples and doesn't require the knowledge of model parameters. It was used to study $PM_{2.5}$ and CO in Fairbanks, Alaska. The effective penetration efficiency for $PM_{2.5}$ ranged from 0.16 to 0.69, and was close to unity for CO. The outdoor generated $PM_{2.5}$ was responsible in average for about 67% of the indoor $PM_{2.5}$ in residences, and close to 100% in office environments.

3.1 Introduction

Fairbanks, in the wintertime, experiences strong ground-based temperature inversions [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 summer time, numerous forest fires in Alaska can as well cause a high concentration of PM in Fairbanks. Both CO and PM are known to have a negative effect on human health [3,4]. Recent studies have shown that fine particles have a higher impact than coarse particles because they penetrate deeper into the lungs. Fine particles are defined as those with the aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). Because of new findings related to the health effects of $PM_{2.5}$, the U.S.

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Environmental Protection Agency decreased the 24-hour standard for ambient air from 65 μg/m^3 to 35 μg/m^3 in September 2006.

People in the United States spend approximately 90% of their time indoors [5] which demonstrates the importance of studying the effect of outdoor air quality on indoor air quality. This percentage is expected to be even higher in the wintertime in Fairbanks. The average indoor concentration of any pollutant can be divided into two components – the concentration caused by indoor sources and the concentration caused by pollution that penetrates from outdoors. The ratio of the latter to the outdoor concentration is usually referred to as the 'effective penetration efficiency' [6] even though some studies use different terms such as the 'infiltration factor' [7]. In the absence of indoor sources, the effective penetration efficiency is equal to the indoor/outdoor (I/O) pollutant concentration ratio.

CO is a relatively stable gas with a lifetime in the atmosphere of approximately 2 months [3]. Therefore, the average indoor concentrations are expected to be the same as outdoor concentrations, or higher if indoor sources of CO are present. The majority of studies support this theory [3], but a couple of studies reported the indoor/outdoor CO concentration ratio significantly lower than one. Chaloulakou et al. [8] reported the I/O CO ratio for a school as low as 0.53 based on daily average values.

$PM_{2.5}$ is subject to filtration as it penetrates into buildings, and subject to deposition on surfaces once inside a building. Because of that, the average indoor concentration of $PM_{2.5}$ in the absence of indoor sources is expected to be lower than the average outdoor concentration. Riley et al. [9] showed that the effective penetration efficiency of airborne particles can vary from 0.05 to more than 0.9, depending on ventilation conditions and other key parameters. Allen et al. [10] found the average $PM_{2.5}$ effective penetration efficiency of 44 residences in Seattle to be 0.65. Morawska et al. [11] studied the I/O ratio in residential environments and found the long-term average values to be very close to one regardless of ventilation conditions and particle size range. Abt et al. [6] studied the effective penetration efficiency in different particle size ranges. The results varied from 0.12 to 0.94 depending on the size range and other parameters.

Measuring the effective penetration efficiency is difficult because it is usually not possible to eliminate the indoor sources for a sufficient period of time. Some studies used the real-time outdoor and indoor concentrations and performed linear regression between them, taking the outdoor concentration as an independent variable. The slope of the regression was used as the estimate of the effective penetration efficiency and the intercept was used as the estimate of the concentration caused by indoor sources. The problem with this method is that it assumes a linear relationship between the indoor and outdoor concentrations. But the relationship between the real-time values is not linear, it is dynamic. The linear relationship applies only to long-term averages or steady-state conditions, which rarely occur. Doing such an analysis using long-term averages would require a very long deployment period in order to obtain a sufficient amount of samples for the linear regression. Other methods use dynamic models to study the transient samples, but these normally require the explicit knowledge of model parameters, such as the ventilation rate or the rate of deposition of a pollutant on surfaces.

This paper presents a method of calculating the effective penetration efficiency from real-time indoor and outdoor pollutant concentrations, using a state-space model. This method does not require the explicit knowledge of model parameters. They are identified from the real-time indoor and outdoor concentrations. Results of using this method to study the effect of outdoor air quality on indoor air in Fairbanks, Alaska are also presented in this paper.

3.2 Methods

Measurements of indoor and outdoor pollutant concentrations were performed at three residential houses (R1 – R3) and four commercial buildings (C1 – C4) in the Fairbanks area between June 2005 and February 2007. Multiple measurements (during different seasons) were performed at several of these buildings, resulting in a total of 12 measurement periods, altogether for the seven buildings. The main focus of these measurements was on CO and $PM_{2.5}$. Indoor smoking was avoided during all of the measurements. During each measurement, outdoor and indoor real-time pollutant levels were measured simultaneously, normally for a period of about two weeks.

Outdoor instruments normally consisted of: TSI 8551 Q-Trak for measuring CO, carbon dioxide (CO_2), temperature (T), and relative humidity (RH); TSI 8520 DustTrak for $PM_{2.5}$; SKC 761-203A Personal Environmental Monitor (PEM) with an SKC 224-PCXR4 pump for the collection of $PM_{2.5}$ on an 0.8 μm polycarbonate filter; EcoChem PAS 2000 CE for PAHs; MetOne 237B Particle Counter for particle counts in 6 size ranges (0.3, 0.5, 0.7, 1.0, 2.0, 5.0 μm); and a HOBO H08-002-02 data logger with TMC6-HA sensor for outdoor temperature. All outdoor instruments were placed in a portable environmental enclosure with a heater and a thermostat (set to 21 °C). The outdoor air was brought to the instruments via tubing. Indoor instruments usually consisted of: TSI 8551 Q-Trak for measuring CO, CO_2, T, and RH; TSI 8520 DustTrak for $PM_{2.5}$; MSP 400 Micro-Environmental Monitor (MEM) for the collection of $PM_{2.5}$ on an 0.8 μm polycarbonate filter; EcoChem PAS 2000 CE for PAHs, MetOne 9012 Particle Counter for particle counts in 6 size ranges (0.3, 0.5, 0.7, 1.0, 2.5, 10.0 μm); and a API 300E Gas Filter Correlation CO Analyzer for accurate CO monitoring (precision: 0.5% of reading, lower detectable limit: 0.04 ppm). Where technically possible (it was possible during 4 measurements), the 300E CO Analyzer was used to measure both indoor and outdoor CO by switching an internal valve between two input ports in one-hour cycles (20 minutes for indoor measurements and 40 minutes for outdoor measurements). The CO Analyzer was placed indoors and the outdoor air was brought to one of the input ports via Teflon tubing. Logging intervals were set differently at different instruments, based on the capabilities of individual instruments, but, in the end, all data were converted into 10-min average samples.

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 properties and other properties (such as particle size distribution) of the measured dust. Therefore, correction factors were applied to the DustTrak values. These correction factors were based on the long-term $PM_{2.5}$ average concentrations determined by gravimetric analyses of the dust collected by the PEM and MEM. The correction factor for the indoor $PM_{2.5}$ was usually around 0.4 and for the outdoor $PM_{2.5}$ around 0.5.

The air exchange rate was estimated for the individual buildings and individual measurement periods from the rate of the CO_2 decay after everyone left the building [12]. It should be noted that this method yields just an approximation of the air exchange rate because it assumes that the outdoor CO_2 concentration is constant during the decay and also that there are no indoor sources of CO_2 (such as plants, pets, pilot lights, etc.), which is rarely completely true.

A dynamic model was used to analyze collected data. The main goal was to calculate the effective penetration efficiencies. Assuming a single-zone situation and a perfect mixing of the air within the zone, the relationship between the real-time indoor pollutant concentration caused by outdoor pollution and the outdoor pollutant concentration can be described using a mass balance equation:

$$\mathrm{d}c/\mathrm{d}t = -(k_v + k + k_d)c + k_v p c_a \tag{3.1}$$

where c is the indoor concentration of the pollutant of outdoor origin; c_a is the outdoor pollutant concentration; k_v is the ventilation rate; k is the decay rate of the pollutant; k_d is the rate of deposition on surfaces; and p is the penetration factor.

Assuming constant k_v, k, k_d, and p, Eq. (3.1) can be expressed using a SISO (Single-Input-Single-Output) state-space model with a single state variable as follows:

$$\mathrm{d}x/\mathrm{d}t = Ax + Bu \tag{3.2}$$

$$y = Cx + Du \tag{3.3}$$

where $A = -(k_v + k + k_d)$; $B = k_v p$; $C = 1$; $D = 0$ are the model parameters; $u = c_a$ is the model input; $y = c$ is the model output; and x is a state variable (an internal variable of the model). In this case $x = c$. This state-space model can be conveniently implemented in MATLAB® on a single line by using the Control System Toolbox® function 'ss(A,B,C,D)'.

The only unknown parameters of the model are A and B. Assuming the component of the indoor pollutant concentration caused by outdoor pollution dominates over the component caused by indoor sources, and assuming correct values for A and B, the output of the model should correlate well with the measured indoor concentration. An important fact is that the parameter B is just a scaling factor and doesn't have any effect on the correlation coefficient between the model output and the measured indoor concentration. Therefore, the parameter A can be estimated by finding such a value of A for which the correlation coefficient between the model output and the measured indoor concentration is a maximum.

Once the value of the parameter A is found, the value of B can be estimated by using the following idea. For the purposes of the following explanations, the difference between the measured indoor concentration and the model output is defined as the 'error concentration'. If the parameters A and B are correct, then the error concentration is equal to the component of the indoor pollutant concentration caused by indoor sources. There is no reason that this component should correlate with the model output. But, if the value of B is chosen too low, the model output will be too low and there will be a positive correlation between the error concentration and the model output. If the value of B is chosen too high then the model output will be too high and there will be a negative correlation between the error concentration and the model output. Therefore, the parameter B can be estimated by finding such a value of B for which the correlation coefficient between the error concentration and the model output equals zero.

Once the parameters A and B are known, the effective penetration efficiency can be calculated as

$$P = -B/A \tag{3.4}$$

where P is the effective penetration efficiency. It is the ratio of the long-term averages of the indoor concentration of the pollutants of outdoor origin and the outdoor pollutant concentration. The same ratio applies to the real-time values of the mentioned variables in steady-state conditions.

It can be shown that the same value of P is obtained by the following procedure. Once A is estimated by the method stated above, B is set to such a value that P equals 1 using Eq. (3.4). Then, a linear regression is performed between the model output and the measured indoor concentration, taking the model output as an independent variable. The slope of the regression is the resulting value of P and the confidence interval of the regression slope is the confidence interval of P. In order to calculate the confidence interval, independent samples are needed. Since the sampling period is 10 minutes, the value of one sample is usually strongly dependent on the value of the previous sample, unless the air exchange rate is very high. For this reason, the decimation of the 10-min samples is performed. The original data is converted to data with the sampling period of three times the time constant of the process. The time constant of the process equals $1/(-A)$, which, in terms of the physical parameters, is the inverse value of the sum of the air exchange, deposition and decay rates.

A program was written in MATLAB® that implements the above algorithm to estimate the A and B parameters of the state-space model and calculates the effective penetration efficiency (the program is available from the authors). The inputs of the program are the measured real-time outdoor and indoor pollutant concentrations, and the outputs of the program are the effective penetration efficiency and the state-space model output, therefore, the real-time indoor concentration of the outdoor generated pollutant. This program was used to analyze the collected CO and $PM_{2.5}$ data.

3.3 Results

One of the assumptions of using the described analysis method is that the ventilation rate is approximately constant during the measurement period. Since some of the monitored buildings had mechanical ventilation systems and since the ventilation rate was not kept constant in certain cases, these cases had to be excluded from the analysis. The data was included in the analysis, though, if a sufficiently long section within the measured data was found when the ventilation rate was approximately constant. Another assumption of this analysis is that the indoor pollutant level is dominated by the pollutants of outdoor origin. This was true for most of the $PM_{2.5}$ measurements, but this was not true in many of the CO measurements because of the effect of attached garages. In one house with an attached garage and no other indoor CO sources in the wintertime, the outdoor average CO concentration was 0.39 ppm while the indoor concentration was 0.91 ppm, therefore, 0.52 ppm higher. Furthermore, the CO data was excluded from the analysis where the outdoor CO concentration was only measured by the Q-Trak because of its poor resolution of 1 ppm. As a result, 8 measurements were used for the $PM_{2.5}$ analysis, and 2 measurements were used for the CO analysis.

The summary of the resulting effective penetration efficiencies for $PM_{2.5}$ is presented in Table 3.1, and for CO in Table 3.2. The measured average indoor and outdoor concentrations are also presented in these tables, together with other variables, such as the indoor/outdoor ratio. The estimated ventilation rates are presented for completeness but, as mentioned earlier, they were not needed for the calculation of the effective penetration efficiencies. Selected graphs, showing the outdoor concentration, indoor concentration and the model output, therefore, the indoor concentration of outdoor origin, are shown in Figure 3.1 – Figure 3.6 for $PM_{2.5}$ and Figure 3.7 for CO.

3.4 Discussion

3.4.1 Discussion of $PM_{2.5}$ results

The resulting values for the $PM_{2.5}$ effective penetration efficiency ranged from 0.16 to 0.69 (see Table 3.1), which agrees with the findings of others [9]. At all residential buildings, the effective penetration efficiency for $PM_{2.5}$ was lower than the indoor/outdoor ratio. This agrees with our expectations because certain residential activities, mainly cooking, are known to produce a significant amount of $PM_{2.5}$ [13]. As seen in Figure 3.1 and Figure 3.3, the model output generally follows the measured indoor $PM_{2.5}$ concentration, except where the indoor concentration is increased by indoor sources. Some increases in the indoor concentration go even above the outdoor concentration, which is a clear evidence of indoor sources. The average contribution of indoor sources to the indoor $PM_{2.5}$ at residential buildings ranged from 0.4 to 6.4 $\mu g/m^3$, which is in the range found by others for nonsmoking homes [12]. The outdoor generated $PM_{2.5}$ was responsible in average for about 67% of the indoor $PM_{2.5}$. Allen et al [10] found it to be 79% for 44 residences in Seattle. The results for home R2 in October 05 are consistent with those in February 06. The contribution of indoor sources was found to be 0.4 $\mu g/m^3$ in both cases, and the effective penetration efficiency was 0.18 in October and 0.19 in February. This consistency supports the idea that the analysis method introduced in this paper is a reliable method and thus suitable for air quality studies of this kind.

In order to further verify the results, the data for home R1 was analyzed using a different method. A short section of the measured data was chosen. This section represents the period from 6/26/05 22:00 o'clock to 6/29/05 16:00 o'clock when no one was present in the house, therefore, a period with no indoor sources. This was during a part of an episode with elevated $PM_{2.5}$ caused by a wild fire in a close-by region of Alaska. This analysis method also uses a state-space model, but the condition to find parameter *B* is that the average measured indoor $PM_{2.5}$ equals the average value of the model output, which means this method assumes no indoor sources. The effective penetration efficiency found by this method based on the three-day period was 0.72, which is in a good agreement with the value of 0.69, which was found by the original method based on the whole 20-day period. It should be pointed out that the original method was also tried on the same three-day period as the modified method. Since there were no indoor sources present, it could be expected that the result would be the same. However, the result for the effective penetration efficiency was 0.45, therefore, significantly different from 0.72. This suggests that the analysis method introduced in this paper provides accurate results only if sufficiently long periods of data are used. The period of three days was too short relative to the time of one air exchange of 10 hours which strongly reduces the number of available independent samples.

At commercial buildings, the effective penetration efficiencies for $PM_{2.5}$ were very close to the I/O ratios (see Table 3.1). This agrees with our expectation that indoor sources are usually limited in office environments because of no cooking activity. The contribution of indoor sources ranged from -0.6 to 0.2 $\mu g/m^3$, therefore, values close to 0 $\mu g/m^3$. The negative values can be either the consequence of a small inaccuracy of the analysis method or it can really be an effect of an occasional negative indoor source, therefore, a sink. Such a sink can be for example an occasional opening of the door between an office and a hallway. Hallways in commercial buildings have usually much lower ventilation rates than offices because their average occupancy is very low. As a result, the $PM_{2.5}$ level is also lower because the lower ventilation rate allows for a bigger effect of deposition on surfaces. It means that opening the door between an office and a hallway can act as a sink.

The measurement in building C4 was the only measurement with absolutely no indoor activity. The instruments were placed in an office which was locked during the whole measurement period. The mechanical ventilation system supplies the office with 100% fresh air (no recirculation) and there is only a supply grille (no exhaust grille), which means the office is pressurized and no pollutants are entering from surrounding zones. The results of the analysis agree with the scenario, the contribution of indoor sources to the indoor $PM_{2.5}$ level was found to be practically zero (see Table 3.1).

If an accurate measurement of the ventilation rates were performed (for example using SF_6 tracer gas), one could theoretically calculate the penetration factor p and the deposition rate k_d from the model parameters A and B, using the relationship $A = -(k_v + k + k_d)$; $B = k_v p$, assuming the $PM_{2.5}$ decay rate $k = 0$. But unrealistic results were obtained using this approach in this study. The penetration factor ranged from 0.1 to 1.1, and the deposition rate ranged from -0.03 to 3.9 h^{-1}. The $PM_{2.5}$ penetration factor found by others is usually in the range from 0.5 to 1 [14-16]. Logically, the penetration factor can never be greater than one, and the deposition rate can never be negative. This is likely due to inaccurate measurements of air exchange rates in our study (using CO_2 as a tracer gas) and also due to inaccuracies in the estimates of model parameters A and B. For example, the value of parameter A was very different in each of the two measurements at building R2 (even though the effective penetration efficiency was almost the same, as discussed earlier). It should be pointed out, that an inaccurate value of the parameter A can still result in an accurate value of the effective penetration efficiency P, due to the principle of the estimation method for parameter B discussed earlier (see the Methods section). The results of this study demonstrate this.

There were two cases (R1 and C1) when the effective penetration efficiency was much higher than in other cases. It was 0.69 in both of these two cases, while the highest value in the other cases was 0.37. These two cases were the only two measurements performed during smoke from nearby wild fires. Our limited data from previous years also suggests that smoke from wild fires has a higher effective penetration efficiency than regular urban $PM_{2.5}$. But more data needs to be collected to draw more certain conclusions.

It should be noted that two studied buildings (see Table 3.1) were naturally ventilated, and the state-space model analysis method was used for these buildings despite the method's assumption of a constant ventilation rate. The ventilation rate of a naturally ventilated building is generally not constant because the air exchange is driven by the stack effect, and thus depends on the outside temperature. This can, for example, result in a big difference between the ventilation rates in summer and winter. However, the length of the measurement periods in this study was usually about two weeks, which means they were not affected by seasonal variations in the outdoor temperature. The short-term variations in the outdoor temperature can still result in fluctuations in the ventilation rate as can opening and closing doors (windows were closed during the measurements). However, the results of this study suggest that the ventilation rate with these fluctuations can be reasonably approximated with a constant ventilation rate.

3.4.2 Discussion of CO results

Only two measurements could be used for the analysis of the effective penetration efficiency for carbon monoxide (see Table 3.2). Both measurements were performed in the same building (C1) at a different time (winter 05-06 and winter 06-07). Even though the I/O ratio in the second measurement period was 1.12 the effective penetration efficiency was found to be 0.99, which is very close to the expected value of 1.00. The value of 1.00 is expected because of relatively good stability of CO, therefore, the penetration factor is expected to be $p = 1.0$ and the deposition and decay rate are expected to be $k_d = k = 0\ h^{-1}$, which, based on Eq. (3.4), results in the effective penetration efficiency $P = 1$. Values close to unity were also shown by the majority of other studies [3].

The I/O ratios in these measurements were higher than 1 even though no known combustion appliances were present in the building. This is most likely caused by the carbon monoxide entering the building from a small 20 minute parking area right at the entrance door. The outdoor CO was measured on the roof of the building, close to the HVAC's intake of fresh air. It means that the CO generated by vehicles at the entrance door was not detected and its passing into the building through the entrance door can be considered an indoor source for our purposes. Based on our activity log (vehicle activity and door-opening activity) and based on the data on vehicle emissions in Fairbanks from Sierra Research [17], it was calculated that the emissions from vehicles in the parking area could certainly be responsible for the measured difference between the indoor and outdoor concentration of 0.05 ppm.

The indoor CO measurements were performed in a staircase with no supply or exhaust grilles from the HVAC system. But our measurements with a hot-wire anemometer showed significant drafts between the staircase and other areas which are served by the HVAC system. The approximate overall air exchange rate of the building was about 1 h^{-1}, which is based on limited data provided to us by HVAC technicians. However, the HVAC system does not operate at night between 10 pm and 6 am. Based on our anemometer measurements of the draft underneath the entrance door (the staircase is right at the entrance door), the air exchange rate at night was estimated to be about 0.2 h^{-1}. It is obvious that the assumption of a constant air exchange rate needed for this analysis method was not met. However, the correlation between the measured indoor concentration and the model output (r = 0.93 in winter 05-06 and r = 0.94 in winter 06-07) suggests that this scenario can still be reasonably approximated with a constant-air-exchange-rate single-zone scenario. The expected air exchange rate of this scenario should be between previously mentioned 0.2 h^{-1} and 1 h^{-1}. Using the CO deposition and decay rate $k_d = k = 0\ h^{-1}$, the air exchange rate k_v was calculated from the model parameter $A = -(k_v + k + k_d)$ as 0.95 h^{-1} in winter 05-06 and 0.63 h^{-1} in winter 06-07. As shown in Table 3.2, the effective penetration efficiency found in winter 05-06 was 1.07, therefore slightly higher than unity. This is probably caused by not completely complying with the assumption of the constant air exchange rate required for this analysis method.

The CO data for building C1 in winter 06-07, for which the state-space-model analysis method found the effective penetration efficiency of 0.99, was also analyzed using a classical approach of the linear regression between outdoor and indoor data, taking the outdoor data as an independent variable. The slope of the regression, representing the effective penetration efficiency, was 0.72, therefore much lower than expected unity . An objective approach to evaluate this method, though, should involve a process of known parameters. For this reason an imaginary building with no indoor sources and constant air exchange rate $k_v = 0.63\ h^{-1}$ was considered. The indoor concentration samples were generated using Eq. (3.1), assuming the deposition and decay rate $k_d = k = 0\ h^{-1}$, and the penetration factor $p = 1$. For outdoor samples, the outdoor CO data measured for building

C1 in winter 06-07 was used. Based on Eq. (3.4), the effective penetration efficiency of this scenario is P = 1.0. However, performing linear regression of the outdoor and indoor samples resulted again in P = 0.72. It is because such an analysis assumes steady-state or long-term average samples and only for such samples can a linear relationship be considered. For transient samples, the regression slope is generally lower than the effective penetration efficiency. It is because of the capacitive character that attenuates quick fluctuations, which means fluctuations of a certain amplitude in the outdoor concentration result in fluctuations of a smaller amplitude in the indoor concentration, therefore, a lower regression slope and a higher intercept. For transient samples, a dynamic relationship between outdoor and indoor concentrations needs to be considered instead of a linear one. The state-space model analysis method was used with the same data as the direct linear regression method. It resulted in the effective penetration efficiency of P =1.00.

3.5 Conclusions

$PM_{2.5}$ and CO were measured outdoors and indoors at several buildings in Fairbanks, Alaska and the data was analyzed using the state-space model analysis method. To the best of our knowledge, this is the first time that this method was used in the area of air quality to study the effective penetration efficiency. It was shown to be a suitable tool for these kinds of studies. The effective penetration efficiency for $PM_{2.5}$ ranged from 0.16 to 0.69 and was close to unity for CO. The outdoor generated $PM_{2.5}$ was responsible in average for about 67% of the indoor $PM_{2.5}$ in residences, and close to 100% in office environments. These results, that are in general agreement with results of other studies, imply that reducing outdoor air pollution can have significant health benefits even for people spending most of their time indoors.

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Table 3.1 Results for the effective penetration efficiencies for $PM_{2.5}$ as found by the state-space-model analysis method

Bldg ID	Mech. Vent.	Measurement period	Vent. rate [h^{-1}]	Avg $PM_{2.5}$ [$\mu g/m^3$]		I/O ratio	Effective Penetration Efficiency*	Indoor $PM_{2.5}$ [$\mu g/m^3$]**	
				outdoors	indoors			From out-doors	From indoor sources
R1	yes	6/22 - 7/12/05	0.10	24.4	23.2	0.95	0.69 (0.55 - 0.82)	16.8	6.4
C1	yes	7/21 - 7/23/05	6.00	16.0	10.4	0.65	0.69 (0.67 - 0.71)	11.0	-0.6
R2	no	10/3 - 10/17/05	0.09	6.4	1.6	0.25	0.18 (-0.2 - 0.56)	1.2	0.4
R3	no	11/16 - 11/30/05	0.13	14.7	6.0	0.41	0.16 (0.04 - 0.28)	2.4	3.6
C2	yes	12/9 - 12/19/05	-	20.2	7.7	0.38	0.37 (0.33 - 0.41)	7.5	0.2
C3	yes	1/24 - 2/8/06	0.90	27.0	5.1	0.19	0.21 (0.19 - 0.23)	5.7	-0.6
R2	no	2/11 - 2/27/06	0.10	10.8	2.5	0.23	0.19 (-0.01 - 0.38)	2.1	0.4
C4	yes	2/16 - 2/20/07	1.10	7.6	1.8	0.24	0.23 (0.20 - 0.25)	1.7	0.1

* Numbers in parentheses represent the 99% confidence interval.
** Components of the indoor $PM_{2.5}$ calculated from the measured outdoor concentration and the effective penetration efficiency.

Table 3.2 Results for the effective penetration efficiency for CO as found by the state-space-model analysis method

Bldg ID	Mech. Vent.	Measurement period	Vent. rate [h^{-1}]	Avg CO [ppm]		I/O ratio	Effective Penetration Efficiency*	Indoor CO [ppm]**	
				outdoors	indoors			From outdoors	From indoor sources
C1	yes	3/3 - 3/16/06	-	0.26	0.28	1.08	1.07 (1.00 - 1.14)	0.28	0.00
C1	yes	12/8 - 12/22/06	-	0.36	0.41	1.12	0.99 (0.90 - 1.09)	0.36	0.05

* Numbers in parentheses represent the 99% confidence interval.
** Components of the indoor CO calculated from the measured outdoor concentration and the effective penetration efficiency.

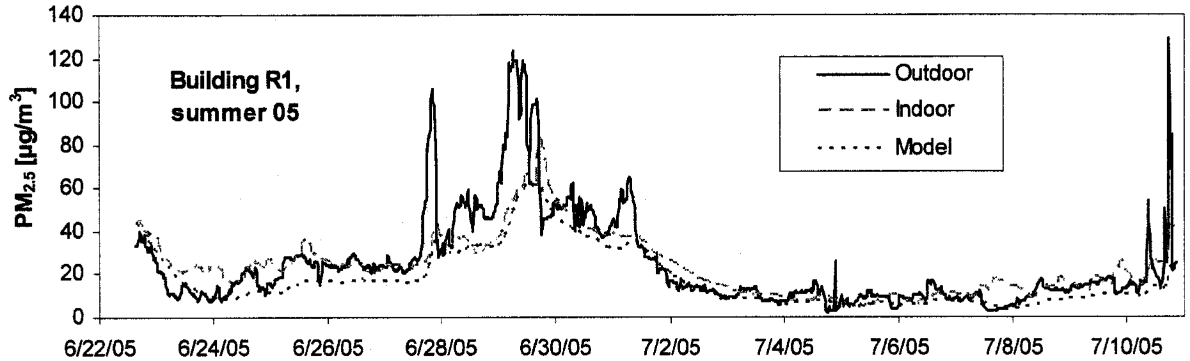

Figure 3.1 Measured outdoor and indoor $PM_{2.5}$, and the model output at building R1 in summer 05

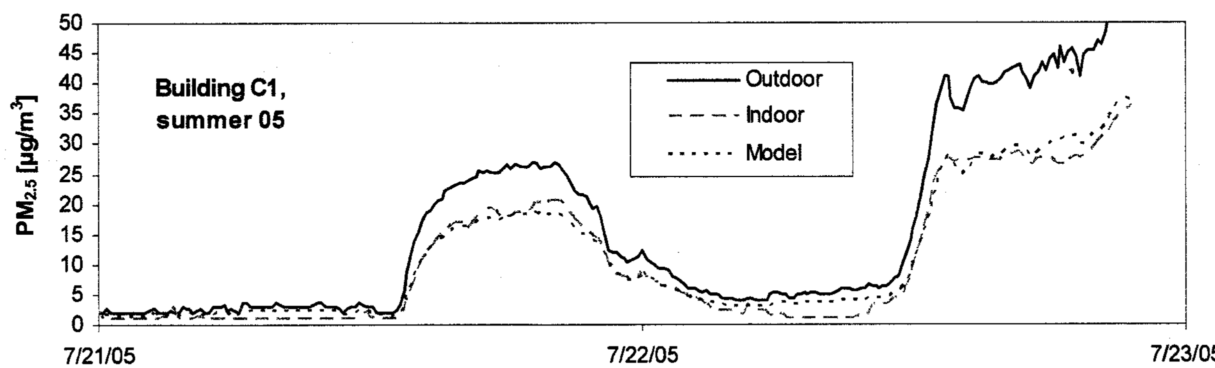

Figure 3.2 Measured outdoor and indoor $PM_{2.5}$, and the model output at building C1 in summer 05

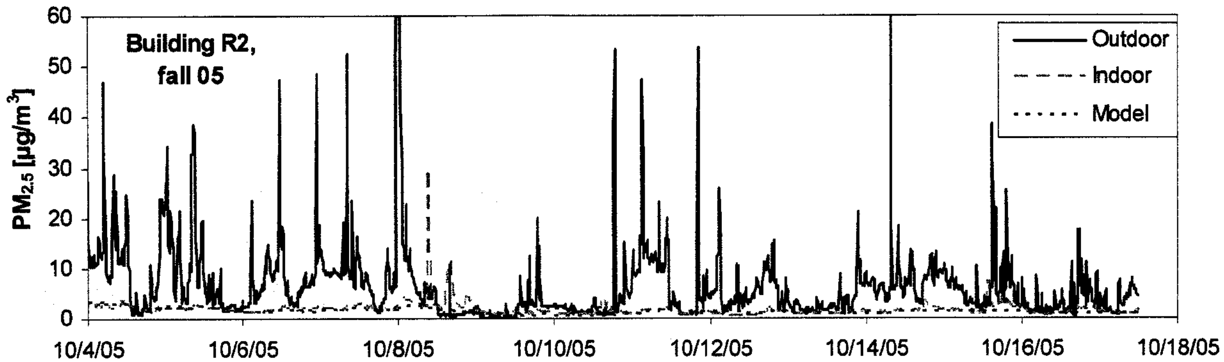

Figure 3.3 Measured outdoor and indoor $PM_{2.5}$, and the model output at building R2 in fall 05

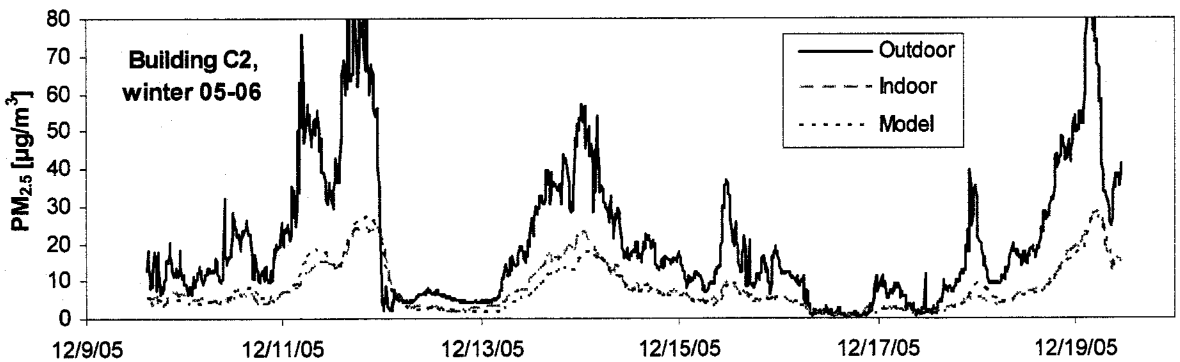

Figure 3.4 Measured outdoor and indoor $PM_{2.5}$, and the model output at building C2 in winter 05-06

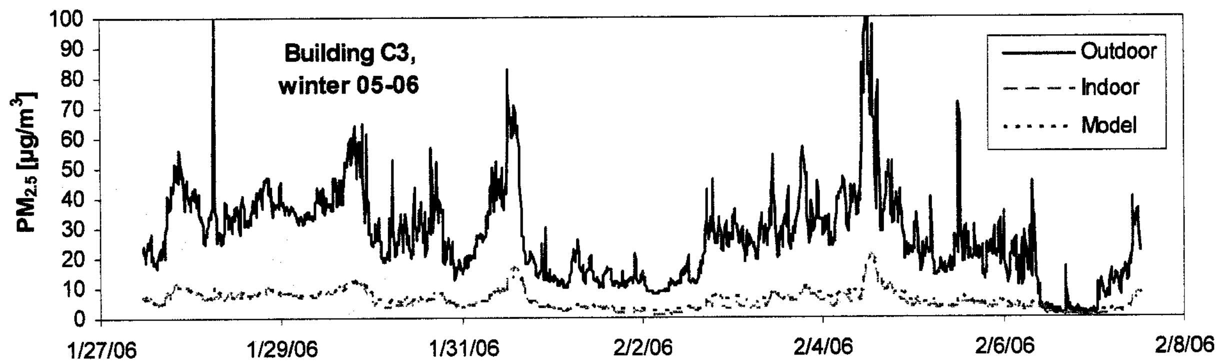

Figure 3.5 Measured outdoor and indoor $PM_{2.5}$, and the model output at building C3 in winter 05-06

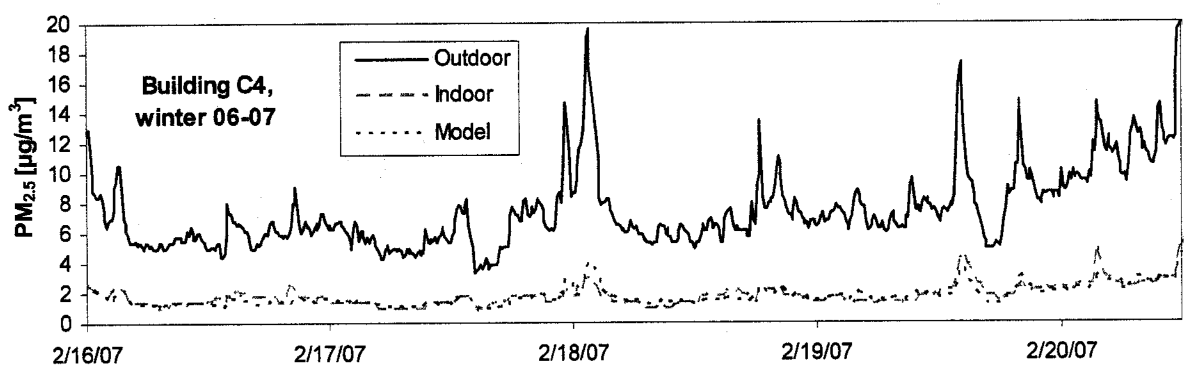

Figure 3.6 Measured outdoor and indoor $PM_{2.5}$, and the model output at building C4 in winter 06-07

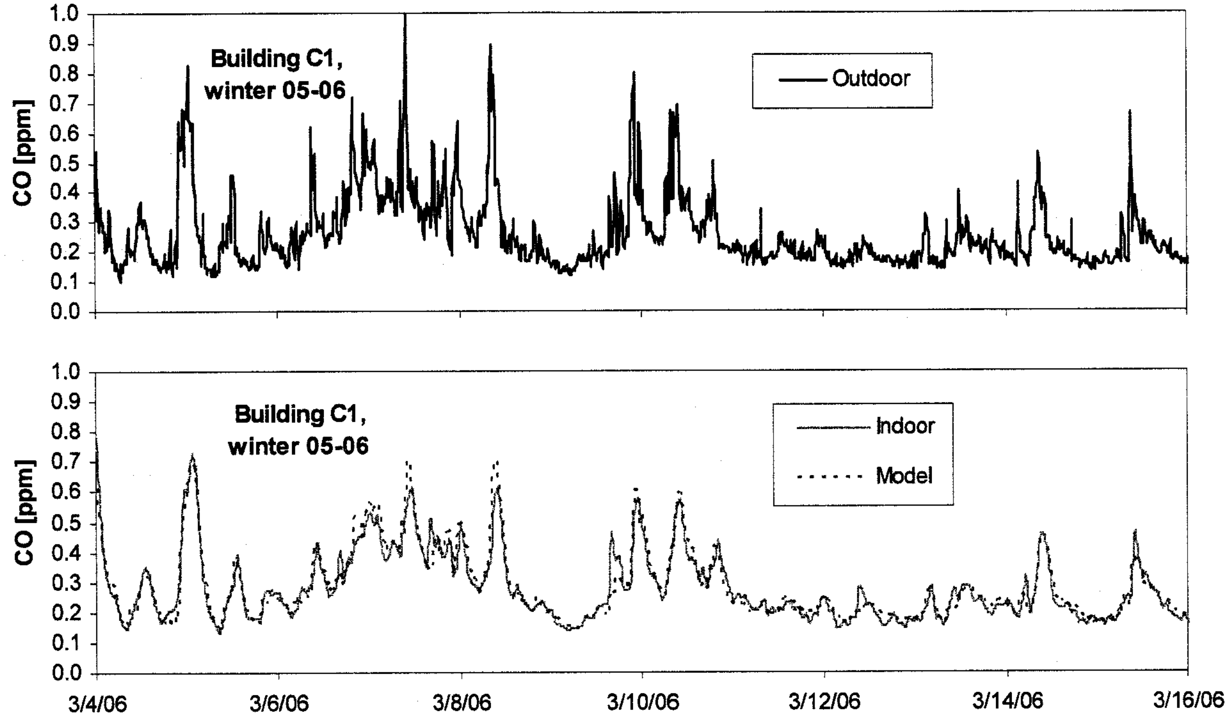

Figure 3.7 Measured outdoor and indoor CO, and the model output at building C1 in winter 05-06

Chapter 4

Simulink® HVAC Air-Quality Model and its Use to Test a $PM_{2.5}$ Control Strategy*

Abstract

This paper presents a MATLAB® Simulink® air-quality model of a commercial building with an HVAC system in Fairbanks, Alaska. Outdoor and indoor real-time $PM_{2.5}$ 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. With 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.

4.1 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 the lungs. Fine particles are defined as those with the aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). Because of new findings related to the health effects of $PM_{2.5}$ [3], the U.S. Environmental Protection Agency

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* T. Marsik and R. Johnson; Submitted to the Building and Environment journal in May 2007

decreased the 24-hour standard for ambient air from 65 μg/m^3 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 nearby 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 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. However, this strategy can have a negative effect on human health 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 simplified way, used an outdoor and indoor CO sensor and reduced the ventilation rate when the outdoor CO level was higher than the indoor one and increased the ventilation rate 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 effected 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 an HVAC (Heating, Ventilation, and Air

Conditioning) system for a commercial building in Fairbanks, Alaska. Measured $PM_{2.5}$ data verifying the validity of the model is also presented in this paper.

4.2 Methods

4.2.1 Data Collection

Two useful data sets were obtained at a campus building at 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 nearby 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 minutes, but, in the end, the data was converted into 10-min averages. Outdoor and indoor real-time CO_2 data was collected using two TSI 8551 Q-Traks to help estimate 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 Figure 4.1. 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 the outdoor $PM_{2.5}$ 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. Since the HVAC system of the studied building uses DDC (Direct Digital Control), it was possible to record the system's variables in 10 minute 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.

4.2.2 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 clarity. The schematic of the HVAC system of the studied building is shown in Figure 4.2, 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 described using a mass balance equation

$$\mathbf{d}\boldsymbol{c}/\mathbf{d}\boldsymbol{t} = [\boldsymbol{p}\boldsymbol{k}_\mathbf{v}(\mathbf{1} - \boldsymbol{m}) - \boldsymbol{k}_\mathbf{v} - (\boldsymbol{k} + \boldsymbol{k}_\mathbf{d})]\boldsymbol{c} + \boldsymbol{p}\boldsymbol{k}_\mathbf{v}\boldsymbol{m}\boldsymbol{c}_\mathbf{a} + \boldsymbol{s} \qquad (4.1)$$

where $k_v = Q / V$ is the air exchange rate, k is the decay rate, k_d is the rate of deposition on surfaces, and s is the indoor source strength. 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 high amount of unknown parameters. Assuming the air exchange, decay, and deposition rates are similar in each room, the multi-zone model can be approximated with a single-zone model.

The controller of the HVAC system in 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 exchange rate. It should be emphasized that, as defined earlier, the air exchange 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 exchange rate of the studied building is about 6 h^{-1}. The deposition rate of $PM_{2.5}$ 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 exchange 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. The decay rate of $PM_{2.5}$, k, can be assumed to equal 0 h^{-1}. 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, $s = 0$ μg/m^3-h was used for our model.

The MERV (Minimum Efficiency Reporting Value) value of the HVAC filter in the studied building is 13. Kowalski et al. [11] 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 μm in 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. (4.1)) 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 Figure 4.3. In this figure, the integration of Eq. (4.1) 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. (4.1). 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% to 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.

4.2.3 $PM_{2.5}$ 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 μg/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 exceeding the indoor target level in steady state. The potential is the highest when no air is recirculated, therefore m = 1. In this situation the following relationship applies to the steady state values:

$$c_{ss} = \frac{pk_v}{k_v + k + k_d} c_{a\text{-}ss} \tag{4.2}$$

where c_{ss} is the indoor steady-state $PM_{2.5}$ concentration and $c_{a\text{-}ss}$ 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/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. If the activation of the $PM_{2.5}$ control strategy were only based on the outdoor level, it would not work for indoor generated $PM_{2.5}$ events or for transients when the outdoor level quickly drops and a large amount of $PM_{2.5}$ is accumulated indoors. 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:

$$c > c_{target} \quad \textbf{OR} \quad c_a > c_{a\text{-}target}$$

where c_{target} and $c_{a\text{-}target}$ 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 the air is being supplied to 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:

$$c_a > c \quad \textbf{then} \quad m = 0.1 \textbf{ or}$$

$$c_a \leq c \quad \textbf{then} \quad m = 1.0.$$

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.

4.3 Results

During the December 2006 measurement, the fresh/recirculated air damper position m varied in the range from about 40% to about 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 Figure 4.4. The model output is almost identical to the measured indoor concentration with the correlation coefficient r = 0.98.

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 $PM_{2.5}$ concentration was measured to be 16.0 $\mu g/m^3$ outdoors and 10.4 $\mu g/m^3$ 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 Figure 4.5. The average indoor $PM_{2.5}$ concentration with the $PM_{2.5}$ control was 3.6 $\mu g/m^3$, therefore, 65% lower than the average indoor concentration with the regular control of 10.4 $\mu g/m^3$. 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.

4.4 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, namely 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. Moreover, the value of 0.68 is above the maximum of 0.6, which was expected based on the model of a MERV13 filter [11], 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 particle-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 $\mu g/m^3$. 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 $PM_{2.5}$ control was 3.6 $\mu g/m^3$, therefore, 65% lower than the average indoor concentration of 10.4 $\mu g/m^3$ with the regular control. Even though it represents only a decrease of 6.8 $\mu g/m^3$ 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 $\mu g/m^3$; 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 should be pointed out, though, that the cooling load is generally small in the summertime 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 due 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. [12] 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 considerations apply to CO_2 levels. Therefore, the minimum ventilation rate (which is determined by the minimum value of m in the $PM_{2.5}$ control strategy presented here) should be based on the dominant indoor pollutant source. Mui et al. [13] 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 determining 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, and other similar factors. In reality, such a control strategy is impossible because there are hundreds or even thousands of pollutants in the air and we only have limited information on their impact on health and comfort [14]. 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.

4.5 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 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 strong 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 indoor levels by 65%. This can have a significant health benefit during episodes with high levels of $PM_{2.5}$, such as during smoke from nearby wild fires.

4.6 Acknowledgements

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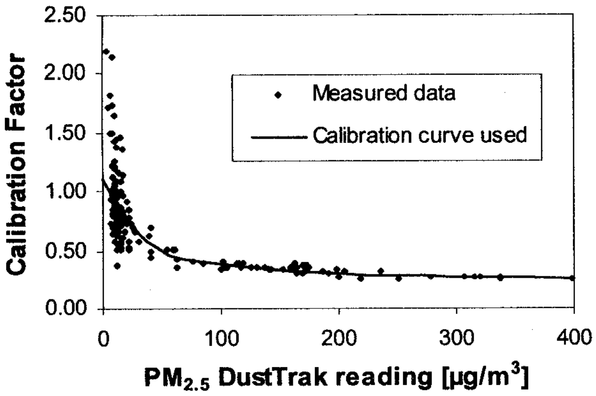

Figure 4.1 DustTrak calibration factor as a function of DustTrak reading as determined by a side by side test with BAM 1020 during wild-fire smoke

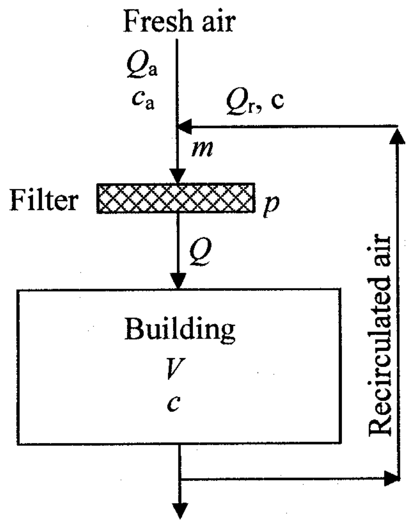

Figure 4.2 Schematic of the HVAC system in the studied building

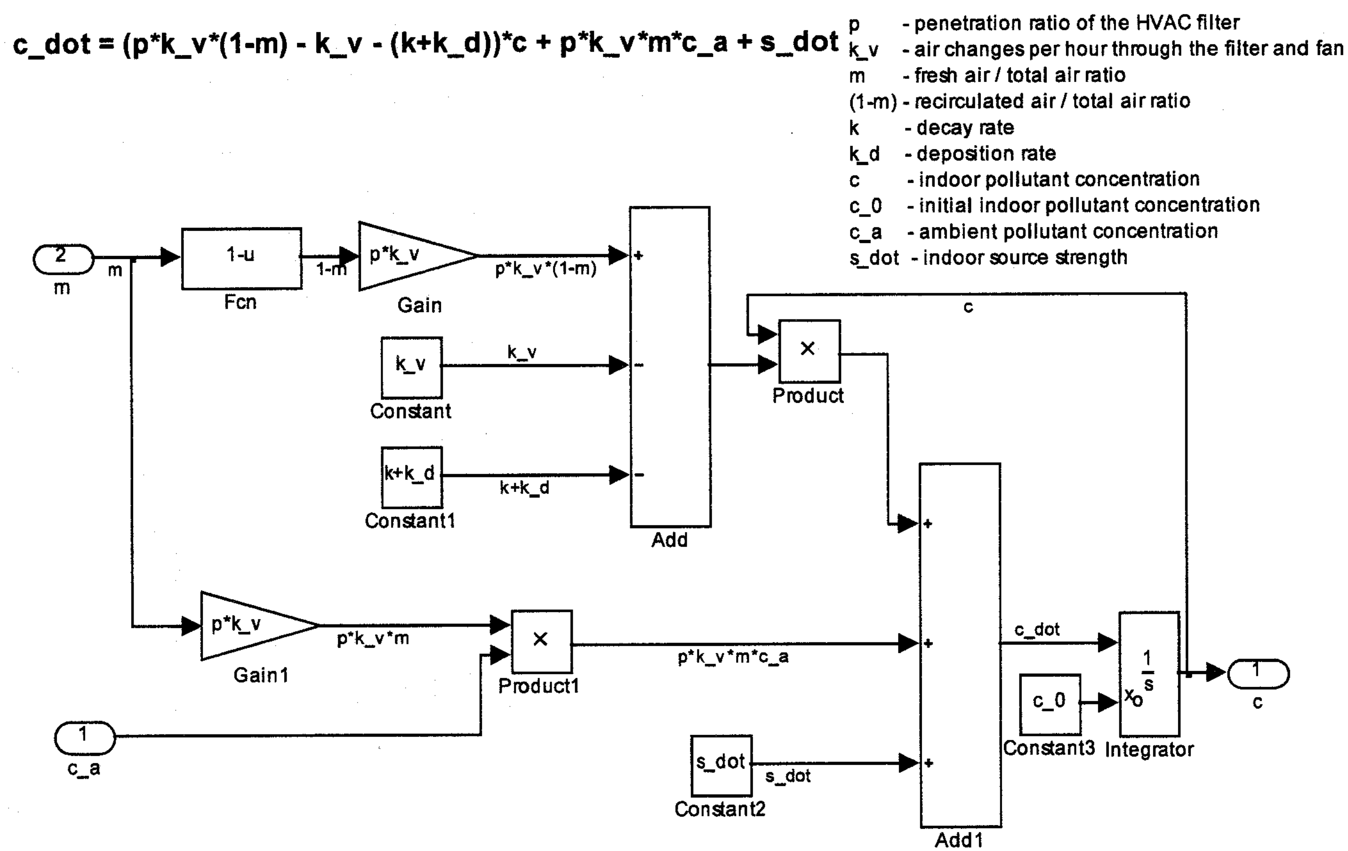

Figure 4.3 MATLAB® Simulink® model of the HVAC system

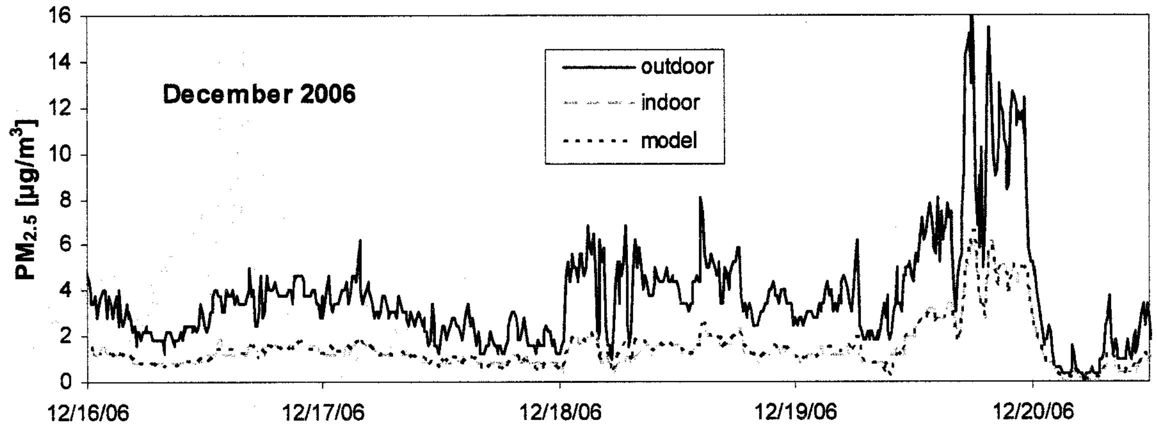

Figure 4.4 Measured outdoor and indoor $PM_{2.5}$ concentrations and the model output in December 2006

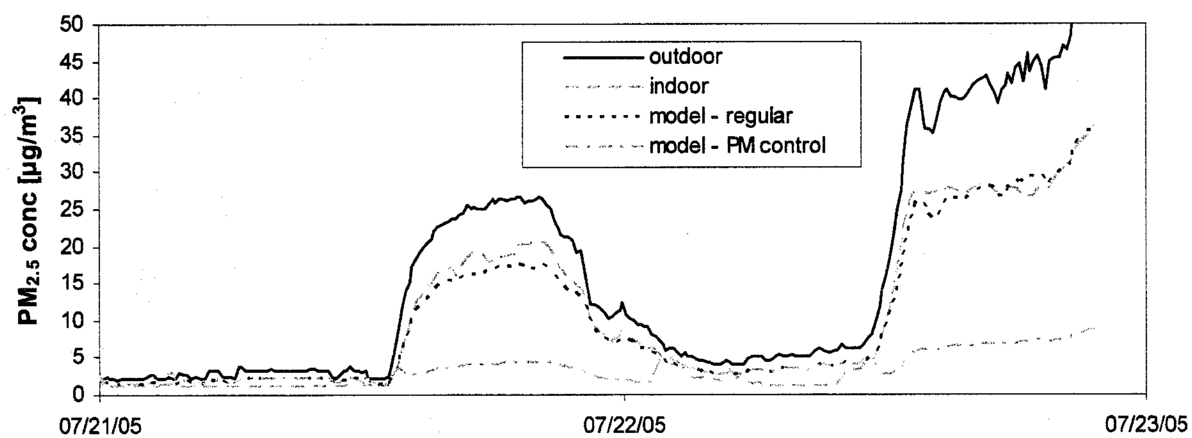

Figure 4.5 Measured outdoor and indoor $PM_{2.5}$ concentrations, model output for regular control and model output for $PM_{2.5}$ control in July 2005

Chapter 5

Use of Simulink® to Evaluate the Air Quality and Energy Performance of HRV-Equipped Residences in Fairbanks, Alaska*

Abstract

Mechanical ventilation systems in residences usually serve a single purpose, providing only a relatively small benefit compared to the capital cost. Polluted areas use mechanical ventilation to filter incoming air, and cold regions use it to be able to recover the heat from the stale air going out. However, both issues – energy and air quality – can be beneficially addressed together using one ventilation system in cold climate regions with air pollution problems, such as Fairbanks, Alaska. This paper presents a dynamic model for evaluating indoor $PM_{2.5}$ levels and energy consumption associated with ventilation. The model was verified by comparing the model-predicted real-time indoor $PM_{2.5}$ level with the actual level measured in a Fairbanks home and a good agreement ($r = 0.95$) was found. Then, the model was used to study three ventilation scenarios of a typical home in Fairbanks – natural ventilation, using an HRV, and using an HRV with an additional particulate filter. The external cost associated with breathing the indoor $PM_{2.5}$ was also evaluated. The scenario with an HRV and an additional filter was shown to have about 380 USD lower annual energy cost than the scenario with natural ventilation and the savings in the $PM_{2.5}$ associated external cost was about 690 USD annually. The savings were shown to exceed the operational costs of the ventilation system.

5.1 Introduction

Increasing costs of fuel and environmental concerns have led to many energy saving measures during the last couple of decades. The area of residential heating has played a big role in this trend. Heat savings are especially important in cold climate regions, such as interior Alaska. Houses are being built tighter and better insulated. Reducing the

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* T. Marsik and R. Johnson; Submitted to the Energy and Buildings journal in May 2007

ventilation rate, though, has resulted in problems with indoor air quality. Pollutants from indoor sources can accumulate inside the building. In addition, reducing ventilation rates increases indoor humidity, which can result in condensation on windows during cold winters and leads to mold formation. People in the United States spend approximately 90% of their time indoors [1], which means it is important to maintain healthy indoor environments. The problem of sufficiently ventilating a house without excessive heat losses has been partially solved by introducing heat recovery ventilators (HRVs). These devices have heat exchangers that transfer heat from the outgoing air into the incoming air.

The problem of balancing indoor air quality and energy consumption is more complicated in Fairbanks because of occasional problems with outdoor air quality. Ventilation strategies often assume that the outdoor air is clean. If the outdoor air is polluted, increased ventilation can increase indoor levels of certain pollutants coming from outdoors. Fairbanks, in the wintertime, experiences strong ground-based temperature inversions [2], and as a result, pollutants released into the air accumulate close to the ground and their concentrations can reach high levels [3]. Carbon monoxide (CO) and particulate matter (PM) are especially of concern. In the summertime, numerous forest fires in Alaska can also cause a high concentration of PM in Fairbanks. Both CO and PM are known to have a negative effect on human health [4, 5]. 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 or less ($PM_{2.5}$). Because of new findings related to the health effects of $PM_{2.5}$, the U.S. Environmental Protection Agency decreased the 24-hour standard for ambient air from 65 $\mu g/m^3$ to 35 $\mu g/m^3$ in September 2006. Based on recent $PM_{2.5}$ measurements, Fairbanks is expected to be in noncompliance with the new standard.

The problem of removing indoor pollutants from a building without bringing other pollutants from outdoors can be partially solved by introducing efficient filters into the mechanical ventilation system. Several studies [6 - 8] have shown that improved filtration can be done with minimal cost. Sultan [9] demonstrated in a case study in Singapore that the cost of improved filtration is small compared to the associated health benefits. Filters have practically no effect on CO, because it is a relatively stable gas [4]. However, CO is a decreasing problem in Fairbanks because of improving emissions from automobile engines and other reasons. $PM_{2.5}$, which is becoming a much bigger problem than CO, can be partially removed by filtration. This paper presents a dynamic computer model that was developed to evaluate various ventilation scenarios with respect to energy consumption and indoor levels of $PM_{2.5}$. Use of this model is demonstrated on a typical building in Fairbanks. Model parameters are based on our measurements at several buildings in Fairbanks in combination with the published findings of others. Three ventilation scenarios are evaluated and compared – natural ventilation, ventilation using an HRV, and ventilation using an HRV with an additional filter. A brief economic analysis of these scenarios, including the external cost associated with breathing indoor $PM_{2.5}$, is performed for these three scenarios.

5.2 Background

As part of a larger study, measurements of indoor and outdoor pollutant concentrations were performed at three residential houses (non smoking) in the Fairbanks area between June 2005 and February 2007. One of the houses was equipped with an HRV. Multiple measurements (during different seasons) were performed at two of these residential buildings, resulting in a total of 5 measurement periods, altogether for the three buildings. The main focus of these measurements was on CO and $PM_{2.5}$. During each measurement, outdoor and indoor real-time pollutant levels were measured simultaneously, normally for a period of about two weeks. The real-time indoor and outdoor data was evaluated using a state-space model analysis method. The results of the analysis form the basis for determining certain parameters of the energy-air-quality model presented in this paper. The analysis details appear in an article titled "Use of a State-Space Model to Study the Effect of Outdoor Air Quality on Indoor Air in Fairbanks, Alaska" that was submitted to the Indoor and Built Environment journal in April 2007.

For pollutants of interest here, assuming completely mixed flow within a building, the relationship between the real-time indoor pollutant concentration and the outdoor pollutant concentration can be described using a mass balance equation:

$$\mathbf{d}c/\mathbf{d}t = -(k_v + k + k_d)c + k_v p c_a + s \tag{5.1}$$

where c is the indoor pollutant concentration; c_a is the outdoor pollutant concentration; k_v is the ventilation rate; k is the decay rate of the pollutant; k_d is the rate of deposition on surfaces; p is the penetration factor; and s is the indoor source strength.

For long-term averaged values, or for real-time values in steady state, Eq. (5.1) can be rewritten as

$$c = pc_a + \frac{s - p(k + k_d)c_a}{k_v + k + k_d}. \tag{5.2}$$

Considering the indoor pollutant concentration c as a function of the ventilation rate k_v, it is obvious that the indoor concentration will be decreasing with increasing ventilation only if the following is true

$$s > p(k + k_d)c_a. \tag{5.3}$$

The relationships in Eq. (5.2) and (5.3) can be used to study $PM_{2.5}$ in Fairbanks residences. Since the average parameters found for Fairbanks homes are based only on three measured buildings, these parameters were adjusted using the findings of others. The average value of the penetration factor p for the Fairbanks residential buildings measured in our study was 0.72. It should be pointed out that none of the three buildings had any filtration system. Thatcher et al. [10] and Ozkaynak et al. [11] have concluded that the penetration factor of fine-mode particles is close to unity. Vette et al. [12]

reported values ranging from approximately 0.5 to 0.8 for 0.01–2 μm particles. The penetration factor of 0.8 will be used for the analysis in this paper.

The average value of the combined deposition and decay rate ($k + k_d$) for Fairbanks residences measured in our study was 0.27 h^{-1}. Ozkaynak et al. [11] reported the mean value of 0.39 h^{-1} for residences in southern California. Abt et al. [13] showed that there can be a tremendous variability in the value of ($k + k_d$). The value of 0.3 h^{-1} will be used for the analysis in this paper.

The average specific indoor $PM_{2.5}$ source strength in Fairbanks homes was found to be 224 μg/h-cap (cap = capita). Stricker Associates [14] studied 30 homes in Quebec, including those with smokers. For the 13 homes with less than 10 cigarettes per week smoked and less than 30 hours per week use of wood in a stove or fireplace, the average specific source strength of $PM_{2.5}$ was 680 μg/h-cap. The value of 400 μg/h-cap will be used for the analysis in this paper. We will consider a characteristic Fairbanks home to have a volume of 540 m^3 (floor area 220 m^2) and 4 occupants. These dimensions and number of occupants will be considered whenever the term "typical Fairbanks home" is used in this paper. This translates the specific source strength of 400 μg/h-cap into the general source strength of 3.0 μg/h-m^3.

The year of 2005 will be used for the analysis in this paper because it is considered to be a typical year in terms of outdoor temperature and $PM_{2.5}$ levels in Fairbanks. Based on the data from the downtown permanent monitoring station, the average annual $PM_{2.5}$ concentration was about 23 μg/m^3. Using this value in the relationship in Eq. (5.3) and using the parameter values as stated above, the right hand side of the relationship results in a value of about 5.5 μg/h-m^3, while the left hand side is equal to 3.0 μg/h-m^3. Since the right hand side is greater than the left hand side, the average $PM_{2.5}$ concentration in a typical Fairbanks home will be rising with increasing ventilation rate, which is the opposite of what one would normally expect to achieve with ventilation. This can also be demonstrated by using Eq. (5.2) and plotting the indoor $PM_{2.5}$ concentration as a function of ventilation rate. This plot, using the parameters for a typical Fairbanks home as stated above, is shown in Figure 5.1. A scenario assuming clean outdoor air (c_a = 0 μg/m^3) is also shown in the graph.

Fairbanks homes are known to have low ventilation rates. Based on the Alaska Building Energy Efficiency Standard (BEES), the minimum air flow provided by a mechanical ventilation system into a residential building is defined as:

$$Q_{fan} = 0.05A_{floor} + 4.7(N_{br} + 1) \tag{5.4}$$

where Q_{fan} is the air flow in L/s, A_{floor} is the floor area in m^2, and N_{br} is the number of bedrooms (assuming two people in the first bedroom and one person in each additional bedroom). This results in the air exchange rate through mechanical ventilation system alone (not including infiltration) of 0.20 h^{-1} for a typical Fairbanks home. The average ventilation rate measured for the three studied buildings was 0.11 h^{-1}. However, as explained above, only increasing the ventilation rate would not completely solve the problem of potential health issues because while certain pollutant levels would decrease, the average indoor level of $PM_{2.5}$ would increase. In order for the $PM_{2.5}$ level to be decreasing with the ventilation rate, the penetration factor p, as calculated from Eq. (5.3), has to be less than 0.43. This implies that the outdoor air has to be filtered before being delivered into the indoor environment.

In order to quantitatively evaluate the benefits of decreasing levels of $PM_{2.5}$ and compare them with associated energy costs and other expenses, a monetary value has to be assigned to the health damage caused by breathing air containing the $PM_{2.5}$. A detailed evaluation of the health effects of various air pollutants was done by the European Commission in a project called ExternE (Externalities of Energy), which is a project focused on estimating external costs associated with different power generation technologies [15]. The health effects of air pollutants were quantified by means of exposure-response functions, which are coefficients that show the average number of cases of a specific health problem induced by the exposure of one person to a unit concentration of a specific pollutant in the ambient air for one year (e.g. 4.33×10^{-6} congestive heart failures per person-year-μg/m^3 of $PM_{2.5}$). Assuming the costs of treatments and other costs in Europe are comparable to those in the USA, the results for the $PM_{2.5}$ external cost can be converted using the rate of 1.362 USD/EUR (exchange rate as of April 29, 2007) to 59.49 USD per person-year-μg/m^3. We will use this value to evaluate the effect of indoor $PM_{2.5}$ in this paper.

5.3 Model Description

A general schematic of building ventilation, including the infiltration through the building envelope, ventilation through windows and ventilation through an HRV is shown in Figure 5.2, where c_a is the ambient $PM_{2.5}$ concentration, T_a is the ambient temperature, T_{supply} is the temperature of the supply air, p_{HRV} is the penetration factor for the particulate filter in the HRV air stream, $k_{v\text{-}HRV}$ is the ventilation rate provided by the HRV, p_{inf} is the penetration factor for the infiltration through the building envelope, $k_{v\text{-}inf}$ is the ventilation rate provided by the infiltration, $k_{v\text{-}win}$ is the ventilation rate through open windows, c is the indoor concentration of $PM_{2.5}$, T is the indoor temperature, and s is the indoor $PM_{2.5}$ source strength. The dashed line represents the optional recirculation of the indoor air through filters. It is assumed that the penetration factor for open windows equals one.

A dynamic model was developed to study the real-time indoor $PM_{2.5}$ concentration and the real-time energy consumption associated with ventilation. The inputs of the model are the real-time outdoor $PM_{2.5}$ concentration and temperature. The outputs of the model are the real-time indoor $PM_{2.5}$ concentration, electric power supplied to the HRV fans, and the heat rate needed to bring the supplied air to room temperature. The model was implemented in MATLAB® Simulink® (files are available from the authors on request); the basic structure is shown in Figure 5.3. The "Human decisions" block represents the typical behavior of residents in Fairbanks with respect to switching their HRVs on or off, activating the recirculation of indoor air, and opening and closing windows, depending on the time of year and outdoor levels of $PM_{2.5}$. The "$PM_{2.5}$ sub-model" performs the calculations of the indoor $PM_{2.5}$ and the "Energy sub-model" calculates the electric and heat power.

Based on Eq. (5.1), the "$PM_{2.5}$ sub-model" uses the following relationship to calculate the real-time indoor $PM_{2.5}$ concentration:

$$\mathbf{d}c/\mathbf{d}t = (p_{\mathrm{inf}}k_{\mathrm{v\text{-}inf}}c_{\mathrm{a}} - k_{\mathrm{v\text{-}inf}}c) + (k_{\mathrm{v\text{-}win}}c_{\mathrm{a}} - k_{\mathrm{v\text{-}win}}c) + (p_{\mathrm{HRV}}k_{\mathrm{v\text{-}HRV}}c_{\mathrm{HRV}} - k_{\mathrm{v\text{-}HRV}}c) + s - (k + k_{\mathrm{d}})c \tag{5.5}$$

where c_{HRV} is equal to c_{a} in normal operation and equal to c in the recirculation mode. Eq. (5.5) represents a general relationship, therefore, it considers the ventilation through infiltration, HRV, and windows at the same time. It can be used for any other ventilation scenario (for example, only infiltration) simply by leaving out the corresponding terms. That is how it is implemented in the Simulink® model, based on the control signals "windows_open/closed" and "HRV_on/off" (see Figure 5.3).

The "$PM_{2.5}$ sub-model" was tested using the measured $PM_{2.5}$ data at an HRV-equipped home in Fairbanks during the 2005 wild fires. Specific parameters of this building were used for the model parameters. The measured outdoor real-time $PM_{2.5}$ concentration was used as the model input. The graphs of the measured outdoor, measured indoor, and model-predicted indoor concentration are shown in Figure 5.4. The model-predicted indoor concentration agrees well (r=0.95) with the measured indoor concentration. The difference between these two is mainly caused by the fact that the model uses a continuous indoor source strength of a constant magnitude (time-averaged value), while in reality the indoor $PM_{2.5}$ source is intermittent.

The "Energy sub-model" calculates the electric power needed by the HRV and the heat rate needed to warm up the incoming air to room temperature. The electric power is equal to the HRV rated power when the HRV is running, and zero when the HRV is off. The fan power variations with the dust loading of the filter are assumed negligible for the purposes of our model since the pressure drop change associated with the variable filter resistance is small. The heat rate is the sum of the heat rates needed to warm up the air coming through the infiltration, windows, and HRV. The heat rate to warm up the HRV-supplied air to the room temperature is:

$$P_{\mathrm{heat}} = Q\rho c_{\mathrm{p}}(T - T_{\mathrm{a}})(1 - \eta_{\mathrm{x}}) \tag{5.6}$$

where P_{heat} is the heat rate needed, Q is the supply air flow, ρ is the air density, c_{p} is the specific heat of air, and η_{x} is the apparent sensible effectiveness of the HRV. It should be noted that P_{heat} represents just the additional heat rate needed after the warm up of the air by the HRV fans; therefore, the apparent sensible effectiveness is used in Eq. (5.6) rather than the sensible recovery efficiency. The electric power of the fans is considered separately, as mentioned earlier. The heat rates needed to warm up the air coming through infiltration and windows to room temperature is calculated similarly to the HRV heat rate (Eq. (5.6)) except that the term $(1 - \eta_{\mathrm{x}})$ is omitted. Home furnace use in Fairbanks is minimal from about June 1 to about August 15. Even on colder days, the solar gain is usually sufficient to keep the house warm. This is implemented in the model by considering the heat rate equal to zero during the mentioned period.

The model was used for a typical Fairbanks home with 3 ventilation scenarios – natural ventilation, ventilation using an HRV, and ventilation using an HRV and an additional filter. As calculated earlier (Eq. (5.4)), the minimum required ventilation rate supplied by a mechanical ventilation system to a typical home in Fairbanks is 0.20 h^{-1}. This BEES ventilation standard was set assuming modern tight houses. The estimated infiltration rate of modern tight houses is typically around 0.05 h^{-1}. This results in the total ventilation rate of 0.25 h^{-1}. This was the total ventilation rate considered in all 3 ventilation scenarios except when the windows are open. The ventilation rate when windows are open can vary over a wide range. However, the exact value is not crucial for this study. Occupants usually open their windows only within the non-heating season and only when the outdoor air is relatively clean. Therefore, the ventilation rate of open windows does not have a big effect on the amount of heat or the $PM_{2.5}$ levels. A ventilation rate of 0.5 h^{-1} is used in our model for open windows.

For the scenario of natural ventilation, therefore without any HRV, the "Human decisions" sub-model (Figure 5.3) was programmed in such a way that the windows are open only in the non-heating season when the outdoor $PM_{2.5}$ level is below 10 $\mu g/m^3$. As mentioned earlier, high summer $PM_{2.5}$ can be caused by wild fires and the level of 10 $\mu g/m^3$ can be detected by smell. The use of the general model for energy consumption and indoor $PM_{2.5}$ for the scenario without any HRV was simply achieved by setting the HRV ventilation rate to zero and the infiltration rate to 0.25 h^{-1}.

For the scenario of the ventilation with an HRV and no additional filters, the "Human decisions" sub-model (Figure 5.3) was programmed in such a way that the windows are open only in the non-heating season when the outdoor $PM_{2.5}$ level is below 10 $\mu g/m^3$. The HRV is on all the time except when the windows are open or when the outdoor $PM_{2.5}$ levels exceed the level of 100 $\mu g/m^3$. The residents of Fairbanks are advised to minimize the intake of outdoor air during episodes of elevated $PM_{2.5}$. This can, of course, have a negative effect on the levels of other indoor pollutants, levels of CO_2, and thermal comfort, but it is a temporary situation and the negative effect can be small with respect to the potential benefit of reduced $PM_{2.5}$ coming from outdoors. The ambient $PM_{2.5}$ levels in Fairbanks during wild fires can exceed 1000 $\mu g/m^3$. The recirculation of indoor air is switched off all the time because recirculation does not have a big effect, unless efficient filters are used. The penetration factor of the HRV, p_{HRV}, was assumed to be 0.8. It is based on our finding for the HRV-equipped home, where we measured the penetration factor of 0.74 and based on the findings of Riley et al. [16] who showed the $PM_{2.5}$ penetration factor of a standard furnace filter to be 0.81. The HRV ventilation rate was assumed to be 0.2 h^{-1}, and the infiltration rate 0.05 h^{-1}.

For the scenario of the ventilation with an HRV and an additional filter, the "Human decisions" sub-model was programmed similarly as in the case of the HRV and no additional filter except that, when the outdoor $PM_{2.5}$ level exceeds 100 $\mu g/m^3$, the recirculation of indoor air through the HRV is activated instead of switching the HRV off. A filter with the MERV (Minimum Efficiency Reporting Value) of 13 was considered for our model. This corresponds to the ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) dust spot efficiency of 80-90%. For urban $PM_{2.5}$, Riley et al. [16] showed the efficiency of an ASHRAE 85% filter to be 64% for outdoor air and 56% for recirculated air. The efficiency for recirculated air is lower because of a modified particle-size distribution such that a larger proportion of the mass is within the lower-efficiency particle size region of the filter. Because the efficiency for outdoor air is relatively close to the efficiency for recirculated air, our model does not differentiate them and uses a general value of 60% (therefore p_{HRV}=0.4) for both.

An HRV with an efficient heat exchanger and efficient fans was considered for both HRV scenarios. The apparent sensible effectiveness η_x was assumed to be 76% and the total power consumption of the fans to be 35 W at the flow rate of 30 L/s (which corresponds to the air exchange rate of 0.20 h^{-1} mentioned earlier). These are realistic values for commercially available efficient HRVs. The indoor temperature was assumed to be 21 °C (70 °F).

For the economical analysis of all scenarios, it was assumed that the house is heated with an oil furnace with the efficiency of 70%. A fuel cost of 0.66 USD per L (2.50 USD per gal) and electricity cost of 0.15 USD per kWh were assumed. As mentioned earlier, the external cost of breathing $PM_{2.5}$ is estimated to be about 59 USD per person-year-$\mu g/m^3$. Since our analysis only deals with the damage cost of breathing the $PM_{2.5}$ at home, this value was multiplied by 0.69 to reflect the fact that one spends approximately 69% of time in a residence. This number is based on the National Human Activity Pattern Survey [1] and reflects the time generally spent in a residence, not necessarily in one's own residence. However, using it in our model also reflects the health damage cost incurred to visitors, not just to the owners of the house. The maintenance cost of the HRV was assumed to be 60 USD per year, reflecting the time spent on the occasional cleaning of the heat exchanger and the standard HRV filter. For the scenario with an HRV and efficient filter, an additional maintenance cost of 40 USD per year is considered to reflect the time spent shopping for and replacing filters. The cost of the MERV 13 filter plus MERV 8 pre-filter is 29 USD. The replacement period of both filters is estimated to be 3 months. The MERV 8 value corresponds to the ASHRAE efficiency of 25 – 30%. Riley et al. [16] showed the efficiency of a 40% ASHRAE filter to be about 8% for typical urban $PM_{2.5}$. Therefore, the efficiency of the MERV 8 filter is even lower and is approximated as zero in our model.

The $PM_{2.5}$ and outdoor temperature data for 2005 was used to perform the simulation for all three ventilation scenarios. This data was obtained from the permanent monitoring station in downtown Fairbanks. The data is in the form of 1-hour averages. For the scenario with an HRV and an efficient filter, the average indoor $PM_{2.5}$ level as a function of the filter efficiency was also studied.

5.4 Results

The summary of the simulation results for a typical Fairbanks home and three different ventilation scenarios are presented in Table 5.1. The ventilation scenarios considered were: natural ventilation (therefore no HRV), an HRV without any additional filter (just the standard filter), and an HRV with an additional MERV 13 filter. The presented data represent the annual values for year 2005. The total energy cost (electricity plus heating oil) associated with ventilation in the scenario with an HRV (310 USD) was 55% lower than the energy cost in the scenario of natural ventilation (689 USD). Considering the annual maintenance cost of 60 USD, the HRV scenario represents an annual saving of 319 USD in the direct costs compared to natural ventilation. The use of a MERV 13 filter in combination with the HRV results in the average indoor $PM_{2.5}$ level of 9.6 $\mu g/m^3$, which is 30% lower than the level of 13.8 $\mu g/m^3$ in the scenario of natural ventilation. The peak indoor $PM_{2.5}$ concentration in the case of the natural ventilation was 359 $\mu g/m^3$, and it was reduced to 88 $\mu g/m^3$ (therefore a reduction of 75%) by using the HRV with the MERV 13 filter. In the HRV scenarios, the additional direct cost of using a MERV 13 filter is 157 USD annually, while the savings in the indirect cost of breathing the $PM_{2.5}$ is 411 USD.

The effect of various filter efficiencies on the resulting annual average indoor $PM_{2.5}$ concentration was studied. It was found that the concentration decreases linearly with increasing filter efficiency. The use of a HEPA (High Efficiency Particulate Air) filter, therefore $p_{HRV} = 0$, would result in the indoor $PM_{2.5}$ concentration of 7.2 $\mu g/m^3$, which would represent the decrease of 2.4 $\mu g/m^3$ compared to the MERV 13 ($p_{HRV} = 0.4$) scenario.

5.5 Discussion of Results

It was shown that a typical home with an HRV has a 55% lower annual energy cost associated with ventilation than the same building ventilated naturally with the same total ventilation rate. Since the sensible recovery efficiency of good HRVs is around 70%, one might expect savings of 70%, rather than the previously mentioned 55%. However, the savings of 70% would be only in an ideal building with no infiltration and with an HRV that does not need any electricity. Even though our model considers the heat supplied by the electric fans, the fact that heating with electricity is more expensive than heating with oil results in a lower savings in the energy cost. However, the realistic savings of 55% in the energy cost still represent a considerable amount of money, approximately 380 USD annually for a typical home presently and probably more in the future due to the rising cost of fuel. 380 USD is not a considerable amount compared to the capital cost of an HRV system. The material cost (including HRV and duct system) is around 2500 USD and one might expect to pay about the same amount additionally for installing it. Plus, one should consider the additional work of making a very tight house, when considering putting in an HRV. All these considerations would result in a long payback period. However, comparing the scenarios of natural ventilation and HRV ventilation based only on this payback period neglects other important factors. Mechanical ventilation generally (not just with an HRV) has significant advantages over the natural ventilation, especially in Alaska. In a naturally ventilated house, the indoor humid air is leaving around window frames and other cracks in the building envelope. In the wintertime, the air is being cooled down as it is passing through the building envelope which may result in condensation. The condensation then results in molds, rotten material, and possibly wet insulation. This phenomenon is seen when dismantling old buildings in Fairbanks. One of the other problems of natural ventilation is a high air exchange rate on cold winter days caused by a significant temperature difference between indoors and outdoors, resulting in a strong stack effect. For these and other reasons, natural ventilation is not considered an acceptable solution for new residences in cold regions. If we assume mechanical ventilation systems will be installed in new buildings anyway, incorporating an HRV does not represent a significant additional expense (HRV units for a typical home cost around 1200 USD), considering the savings in the energy cost. Another important consideration is the reduced emissions of greenhouse gases, mainly CO_2, associated with the reduced fuel consumption.

It was shown that even a mechanical ventilation system without additional filters can have a positive effect on indoor levels of $PM_{2.5}$. This is because having a tight house with a mechanical ventilation system allows people to strongly reduce the ventilation rate by switching off the ventilation during episodes of very high outdoor levels of $PM_{2.5}$. Another advantage is the possibility of increasing the ventilation rate by switching the fans to a higher speed during indoor activities producing higher amounts of indoor pollutants (such as cooking) or increasing significantly the indoor humidity (such as showering), even though this feature is not incorporated in our model.

Table 5.1 shows that incorporating a MERV 13 filter into an HRV system can result in the total savings of about 250 USD annually. This scenario assumes that there is a filter housing with a bigger cross-sectional area (to reduce the pressure drop) incorporated into the duct system. This housing represents about 500 USD more in the capital cost of the ventilation system, which is not a significant amount considering the annual savings. Plus, having the filter housing allows for using other filters, not just for PM. Activated carbon filters can be used to decrease VOC levels, which can be especially useful during wild fires.

The main uncertainties of our model should be addressed; however, their quantification was beyond the scope of our work. There are some uncertainties in the model parameters, such as the deposition rate and penetration factor, as discussed earlier. Other uncertainties are in the ventilation use patterns, for example, some people ventilate permanently using an HRV even in the non-heating season. Another uncertainty is in the evaluation of the peak indoor $PM_{2.5}$ levels, especially in the case of natural ventilation. Our model assumes a constant infiltration rate of a naturally ventilated building throughout the year, but the infiltration rate is higher in the wintertime because of the stack effect. The biggest uncertainty to address is the one associated with the external cost of breathing the indoor $PM_{2.5}$. Our model uses exposure-response functions that were developed based on outdoor $PM_{2.5}$, and their use for indoor $PM_{2.5}$ needs to be verified. Also, these exposure-response functions were developed for typical ambient $PM_{2.5}$ in Europe. A significant portion of the $PM_{2.5}$ that our model is used for is formed by smoke from wild fires, which can have a different effect on human health than the $PM_{2.5}$ discussed above.

5.6 Conclusions

An energy-air-quality dynamic model of a residential building was presented and its use was demonstrated on a typical residential building in Fairbanks. It was shown to be a suitable tool for the analysis of indoor levels of $PM_{2.5}$ and the energy consumption associated with ventilation. Three ventilation scenarios were evaluated using the model – natural ventilation, ventilation using an HRV, and ventilation using an HRV with an additional MERV 13 filter. Ventilation using an HRV was shown to save about 380 USD annually in energy costs. Using an HRV with an additional filter was shown to save about 690 USD in the health damage cost associated with breathing indoor $PM_{2.5}$ compared to using natural ventilation, even though uncertainties exist in the evaluation of the health damage cost. The benefits of using an HRV with an additional filter were shown to strongly exceed the operational costs of such a ventilation system. Overall, ventilation using an HRV with an additional filter was found to be the best solution with respect to the energy cost, indoor air quality, and also outdoor environment due to the decreased amount of fuel use and associated greenhouse gas emissions.

5.7 Acknowledgements

This work was done at the Institute of Northern Engineering, University of Alaska Fairbanks, and was supported by the Fairbanks North Star Borough and the US Environmental Protection Agency. The authors would also like to thank Phil Loudon with the Arctic Technical Services, Bill Reynolds with the Solutions to Healthy Breathing, and John Davies with the Cold Climate Housing Research Center for their valuable inputs.

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Table 5.1 Results for studied scenarios showing the $PM_{2.5}$ levels, direct costs (excluding initial capital costs) associated with ventilation, and indirect costs associated with breathing the indoor $PM_{2.5}$ for 2005

	Natural vent.	HRV	HRV & filter
Outdoor avg $PM_{2.5}$ [μg/m^3]	23.2	23.2	23.2
Indoor avg $PM_{2.5}$ [μg/m^3]	13.8	12.1	9.6
Peak indoor $PM_{2.5}$ [μg/m^3]	358.7	114.1	87.9
Cost of heating oil [USD]	689	268	268
Cost of electricity [USD]	0	42	43
Total energy cost [USD]	**689**	**310**	**311**
Maintenance cost [USD]	0	60	100
Cost of filters [USD]	0	0	116
Total direct cost [USD]	**689**	**370**	**527**
$PM_{2.5}$ external cost [USD]	**2266**	**1987**	**1576**
Total cost [USD]	**2955**	**2356**	**2103**

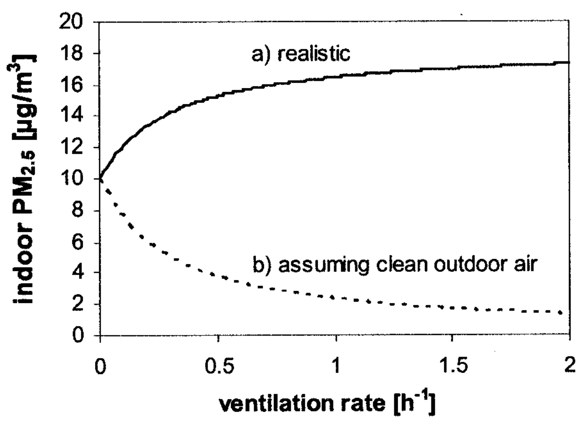

Figure 5.1 Indoor $PM_{2.5}$ as a function of ventilation rate for a typical Fairbanks home; a) Realistic scenario with true outdoor $PM_{2.5}$; b) Scenario assuming clean outdoor air

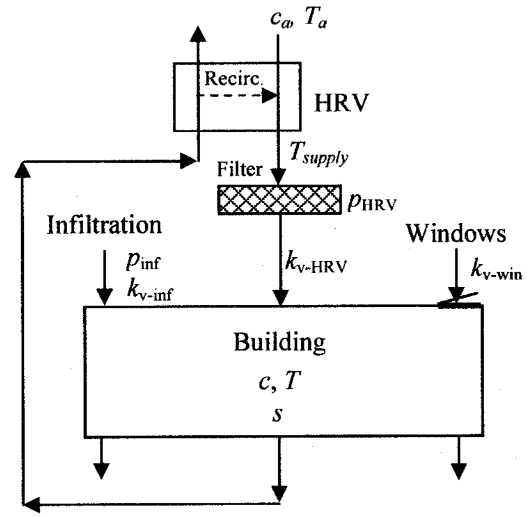

Figure 5.2 Schematic of building ventilation

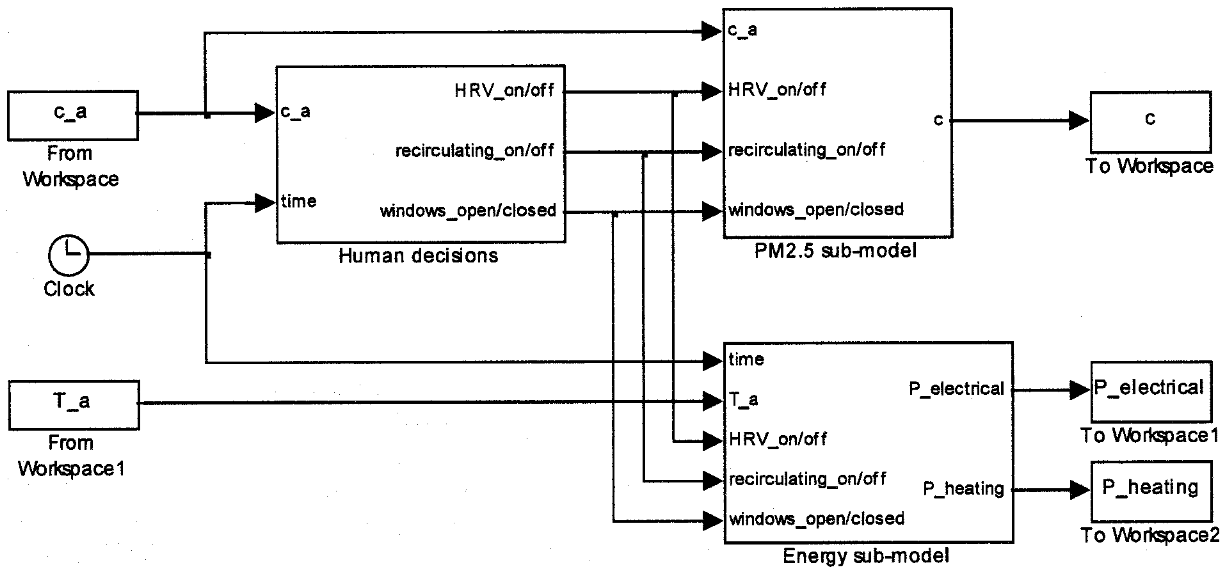

Figure 5.3 Basic structure of the Simulink® model for building ventilation

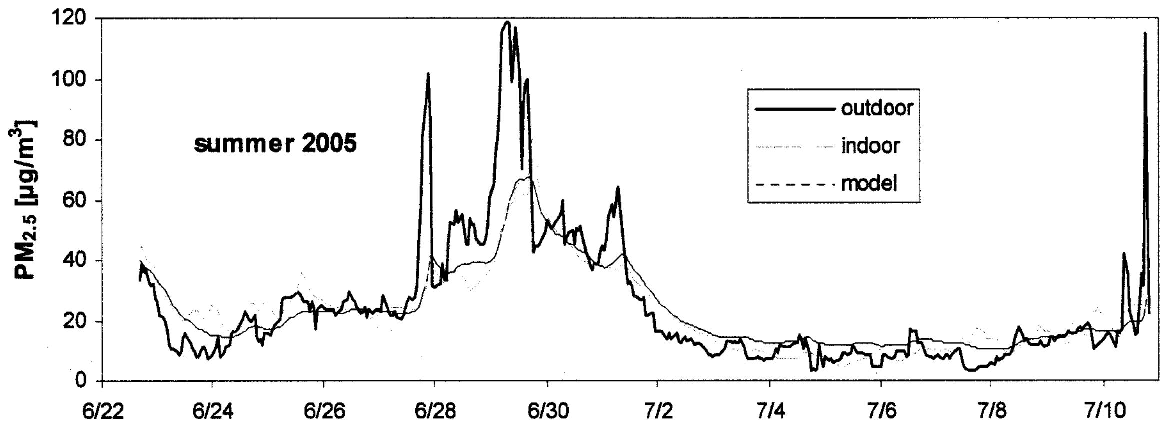

Figure 5.4 Measured outdoor, measured indoor, and model-predicted indoor $PM_{2.5}$ concentration at an HRV-equipped residential building

Chapter 6
Use of Simulink® to Address Key Factors for Radon Mitigation in a Fairbanks Home*

Abstract

Hilly areas around Fairbanks, Alaska are known to have elevated soil radon concentrations. Due to geological conditions, cold winters and the resulting stack effect, houses in these areas are prone to higher indoor radon concentrations. Key variables with respect to radon mitigation were addressed in this paper by using a dynamic model implemented in MATLAB® Simulink®. These variables included the ventilation rate; the foundation flow resistance which can be affected by sealing the foundation during the construction of a house; and the differential pressure between the subslab and the house interior which can be affected by using a subslab depressurization system. The model was used for the scenario of a varying differential pressure and then for the scenario of a varying ventilation rate at a Fairbanks home where real-time radon concentrations were measured. The correlation coefficients between the model-predicted and measured radon concentrations were 0.96 and 0.94, for both scenarios, respectively, which verified the feasibility of the model for predicting indoor radon concentrations.

6.1 Introduction

Indoor air quality is affected by a host of factors. These include the quality of the outdoor air, indoor sources and sinks, the air quality in the soil underneath the house, and the airflow between the ambient environment and the building. Ambient can include both above ground and below ground.

Radon, arising from the decay of uranium, is a naturally occurring radioactive gas found in pores in the soil at concentrations sometimes exceeding 1,000 pCi L^{-1} (Nero 1989)

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* T. Marsik and R. Johnson; Submitted to the Health Physics journal in May 2007

(ambient air concentrations are typically < 1 pCi L^{-1}). Radon-222 is the isotope of concern and its progeny, polonium-218 and 214 are of concern because they emit alpha particles, which can cause lung cancer. The recommended maximum annual indoor average is 4 pCi L^{-1}, with 7% of homes in the US and 30% in the hills around Fairbanks estimated to exceed this (Johnson et al. 2002). High concentrations that sometimes occur in homes are due mainly to elevated radon entry rates caused by the stack effect creating a few pascal lower pressure in the basement than in the subslab soil. The final indoor concentration is determined by a balance between the radon generation rate, the soil-gas entry rate, and the ventilation rate. The recommended maximum level indoors is 4 pCi L^{-1} and there are probably 100,000 homes in the US with levels above 10 pCi L^{-1} and 1 M with levels exceeding 8 pCi L^{-1} (Nero 1989). One pCi corresponds to 2.2 disintegrations per minute.

In the absence of radon emitting materials within a dwelling, critical variables are the concentration of radon in the ground underneath the house, the permeability of the subsurface, the magnitude and sign of the pressure difference between the subsurface and the house interior, and the air exchange rate between the house and ambient. Sometimes undesirable levels of volatile organic compounds can migrate into the house from the subsurface by the same mechanism as radon. This can be a problem when there have been underground fuel spills.

Hilly areas around Fairbanks, Alaska are known to have elevated soil radon concentrations. Because of our cold climate and the stack effect resulting from the high temperature difference between outdoors and indoors, homes in these hilly areas around Fairbanks are susceptible to higher indoor radon concentrations. Results from past studies conducted by others (Hawkins et al. 1987; Nye and Kline 1990) as well as ourselves indicate that 20 to 45% of the homes without radon mitigation systems surveyed in the hilly areas had indoor radon levels exceeding the US EPA (Environmental Protection Agency) limit of 4 pCi L^{-1}. In 16 out of 18 houses with radon mitigation systems, radon levels were reduced by at least 73%.

Johnson et al (2005) used a transient mass conservation model in a Simulink® platform to predict the rise in indoor radon in a Fairbanks home with the radon source strength being proportional to subslab radon concentration. Janssen (2003) estimated indoor radon levels for conditions representative of newly built Dutch homes. Lembrechts et al (2001) showed the most important radon source in new (very tight) Dutch homes was the building materials. Besides collecting field data, they calculated radon concentrations using two coupled models. One calculated pressure differences and flows within the dwelling while the other predicted source strengths for both the soil and the building materials. A critical variable in each of these studies was the ventilation rate. Low ventilation rates can lead to elevated indoor radon levels. Scott (1992) pointed out that high radon concentrations were caused by unusual soil conditions rather than by building type based on data from thousands of homes in the US and Canada. Although less than 1% of these "normal" houses had indoor radon levels > 1 pCi L^{-1}, in some districts more than 20% did. He found the soil radon potential could be estimated from the airflow resistance I_s of the soil around the house foundation together with the radon concentration C_s in the soil pores near the foundation. For a rectangular basement, I_s varies inversely with soil permeability. The driving force was the pressure difference between the soil surface and the foundation openings. In conventional house basements, the foundation resistance was negligible compared with the soil resistance. The Radon Generation, Entry and Accumulation Indoors (RAGENA) model (Font and Baixeras 2003) solves a set of coupled differential equations to account for various radon sources, entry processes, ventilation, and occupant behavior. The sources include the soil, building materials, and water. It was applied successfully to a house in a Mediterranean climate under dynamic conditions.

Our recent study, presented in this paper, extends the previous work by incorporating the differential pressure between the subslab and basement of a building into the transient model. The feasibility of the model is verified by comparing the model-predicted real-time indoor radon concentrations with the measured concentrations.

6.2 Methods

An extensive radon measurement was performed at a new Alaskan home between June 2005 and October 2006. The house is located in the hills west of Fairbanks. It has 2 stories, plus a basement. The foundation consists of gravel bedding over fractured schist, perforated pipes, 6-mil polyethylene, polystyrene insulation and a poured slab. The polyethylene is continuous under the footing and all penetrations are sealed. The house has a heat recovery ventilator (HRV). An active subslab depressurization (ASD) system was installed in February 2006, therefore in the middle of our radon measurements. The radon measurements were performed in five individual measurement periods; the average length of one period was about 2 months. During most of these periods, two RSSI Alpha-track detectors and two Sun Nuclear Continuous Radon Monitors (CRMs) were deployed, one of each in the basement and one of each on the first floor. The Alpha-track measures accurately the average radon concentration over the whole deployment period. The CRM is less accurate, but it allows for a near real-time measurement of the radon concentration. The CRM logging interval was usually set to 24 hours, but in certain cases a shorter interval was used to allow us to better study transient concentrations.

The differential pressure between the subslab and basement was measured for a period of about one week in the winter. This was before the ASD system was installed with the pipe coming from the subslab capped right above the basement floor. This setup allowed us to drill a hole in the cap and insert a piece of tubing through it. This tubing was then connected to an OMEGA PX274 differential pressure transducer, the output of which was being recorded with an Onset HOBO H08-002-02 data logger. The house occupants kept a log of the HRV and ASD settings. The HRV settings allowed us to determine the ventilation rates at given periods. The ventilation rates were calculated based on the HRV rated flows at individual settings and the house volume. The infiltration rate of 0.05 h^{-1} was considered in addition to the mechanical ventilation, which resulted in the total ventilation rate of 0.43 h^{-1} for the "max", 0.23 h^{-1} for "min" and 0.11 h^{-1} for "intermittent" HRV settings.

A dynamic model was used to study the effect of key variables on the indoor radon concentration. Assuming completely mixed flow within the studied zone, the general mass-balance equation for a pollutant can be written as:

$$\mathbf{d}\boldsymbol{c}/\mathbf{d}\boldsymbol{t} = -(\boldsymbol{k}_\mathrm{v} + \boldsymbol{k} + \boldsymbol{k}_\mathrm{d})\boldsymbol{c} + \boldsymbol{k}_\mathrm{v}\boldsymbol{p}\boldsymbol{c}_\mathrm{a} + \boldsymbol{s} \tag{6.1}$$

where c is the indoor pollutant concentration; c_a is the outdoor pollutant concentration; k_v is the ventilation rate; k is the decay rate of the pollutant; k_d is the rate of deposition on surfaces; p is the penetration factor; and s is the indoor source strength. For radon, the assumed values in this paper are k=0.0075 h^{-1}, k_d=0 h^{-1}, p=1, and c_a=0.1 pCi L^{-1}.

Even though the radon coming into the house from the underlying soil is produced by an outdoor source, it can be considered an indoor source for modeling purposes. It is assumed that no other indoor sources are present. Treating the basement as a separate zone, the indoor source strength in this zone can be expressed as:

$$s = \frac{c_s \Delta P}{V I_f} \tag{6.2}$$

where c_s is the subsurface radon concentration; ΔP is the differential pressure between the subslab and the basement; V is the basement volume; and I_f is the foundation air flow resistance.

A dynamic model was made based on Eq. (6.1) and Eq. (6.2). The inputs of the model are the real-time ventilation rate, k_v, and the real-time differential pressure, ΔP. The output of the model is the real-time radon concentration in the basement, c. The model was implemented in MATLAB® Simulink® (files are available from the authors on request) and is shown in Figure 6.1. In this figure, the integrator block in the lower right-hand corner calculates the indoor concentration, c, from its derivative, dc/dt. The blocks to the left represent the mathematical operations needed to calculate dc/dt as defined by Eq. (6.1) and Eq. (6.2).

The model was used with the real-time differential pressure data, ΔP, collected at the house in the winter. The ventilation rate, k_v, was kept constant during the simulation because the HRV was set to "intermittent" during the whole period. The model parameter $c_s/(VI_f)$ was calculated from the measured ΔP and c during a quasi-steady state that occurred during a part of the measurement, using Eq. (6.2) and the following relationship for steady-state values:

$$c = \frac{k_v p c_a + s}{(k_v + k + k_d)}. \tag{6.3}$$

The HRV settings were changed several times for research purposes during about a one-month period in the summer of 2006. The ASD system was running during the whole period. The model was used for this period with the real-time ventilation rate as determined from the log of HRV settings. The indoor source strength, s, was assumed constant during the simulation because of a leak in the ASD system (discussed below), which was assumed to be the major indoor radon source. This is different from the above wintertime case in that now s is constant while k_v varies. The value of s was calculated using Eq. (6.3) from the measured c and known k_v during a quasi-steady state that occurred during a part of the measurement. Because the Simulink® model (Figure 6.1) does not have an explicit input for s, s was input through the ΔP input by setting the value of $c_s/(VI_f)$ to unity. The model-predicted real-time basement radon concentrations were compared with the measured concentrations.

In order to evaluate a suspected leak in the ASD system, the following analysis was performed. Basement radon levels for various periods with constant settings of the HRV and ASD systems were taken and using the mass-balance equation for steady state (Eq. (6.3)), these levels were recalculated into levels that would have been there if the HRV had been running in the intermittent mode. Then, these values were grouped into two categories: the first group representing the levels when the ASD was off and the second group representing the levels when the ASD was on. These radon levels were plotted as a function of outdoor temperature and compared. This was done because the outdoor temperature was considered the main meteorological factor affecting indoor radon levels, even though other factors, such as barometric pressure, exist (Robinson et al. 1997). The outdoor temperature data was obtained from the Fairbanks International Airport.

6.3 Results

The overall average radon concentration based on the alpha-track measurements was 16.1 pCi L^{-1} in the basement and 5.3 pCi L^{-1} in the living area. The Simulink® model was used to predict the real-time basement radon concentration during the one-week period in winter when the differential pressure between the subslab and the basement was measured. The differential pressure, measured basement radon concentration, and model-predicted concentration are shown in Figure 6.2. The correlation coefficient between the differential pressure and the measured radon concentration is 0.80, while the correlation coefficient between the measured radon concentration and the model-predicted concentration is 0.96.

The Simulink® model was also used to predict the real-time basement radon concentration during the summer period when the HRV setting was changed several times. According to the log that the occupants kept, the HRV was in the "intermittent" mode, then it was turned "off", then it was switched to the "intermittent" mode again, and then to the "continuous max" mode. The ASD system was "on" during the whole period. The measured basement radon concentration and the model-predicted concentration are shown in Figure 6.3 and the correlation coefficient is 0.94.

Figure 6.4 shows the basement radon concentration as a function of outdoor temperature when the ASD system was "off" (Figure 6.4a) and when the ASD system was "on"

(Figure 6.4b). The radon concentrations shown are the values using the HRV in the "intermittent" mode.

6.4 Discussion

Relatively high radon concentrations were found in the studied house. The overall average radon concentration based on the alpha-track measurements was 16.1 pCi L^{-1} in the basement and 5.3 pCi L^{-1} in the living area, which are values exceeding the US EPA limit of 4 pCi L^{-1}. As seen in Figure 6.4, with the ASD system "off" and the outdoor temperatures around -15 °C, the basement radon concentration can reach around 150 pCi L^{-1}, therefore almost 40 times higher value than the standard of 4 pCi L^{-1}. The corresponding radon concentration at the same outdoor temperature with the ASD system "on" is about 6 pCi L^{-1}, which represents about a 96% decrease from the value with the ASD system "off". An important thing to notice is that for outdoor temperatures close to 20 °C, therefore when the stack effect is small, the radon concentration with the ASD system "on" (around 3 pCi L^{-1}) is higher than with the ASD system "off" (around 0.5 pCi L^{-1}). Based on this analysis, a suspected leak in the ASD system was communicated to the owners of the house. They checked the pipes of the ASD system downstream of the fan and discovered that one joint was not glued and likely leaking.

As seen in Figure 6.2, the real-time basement radon concentration, c, was well predicted based on the real-time differential pressure between the subslab and the basement, ΔP, and based on the known ventilation rate, k_v. The correlation coefficient between the model-predicted and measured radon concentration is 0.96. It should be noted that the correlation coefficient between ΔP and c is only 0.80. It demonstrates that a dynamic model needs to be used to study the correlation between ΔP and c. Because the Pearson's correlation coefficient assumes a linear relationship, and the relationship between ΔP and c is not linear, use of a dynamic model is advantageous. As seen in Figure 6.1, ΔP varied between about 1.5 Pa and 4.5 Pa. This is in the order of values for the differential pressure between outdoors and the basement induced by the stack effect. It means that, in this case, the foundation flow resistance is not negligible with respect to the soil flow resistance, as would be expected for conventional houses (Scott 1992). The foundation flow resistance of this house was strongly increased by sealing it during construction as discussed earlier. Moreover, the subslab soil resistance is at the low end of values we have encountered because of the presence of fractured schist. The fact that ΔP was shown to be one of the determining factors for indoor radon levels justifies the use of ASD systems, which decrease ΔP.

As seen in Figure 6.3, the real-time basement radon concentration was reasonably well predicted based on the known ventilation rate. The correlation coefficient between the model-predicted and measured concentration is 0.94. The difference between the two concentrations is likely caused by the fact that the radon source strength was assumed constant. Even though the majority of the radon was probably coming from the leaking ASD pipe, some portion was likely still infiltrating through the foundation. This portion is affected by meteorological parameters, such as temperature and barometric pressure (Robinson et al. 1997), which can not be assumed constant. Another factor might have been an increased activity in the basement and frequent opening of the basement door.

6.5 Conclusions

The relationship between key variables and indoor radon concentrations was verified by using a dynamic model and comparing the model-predicted real-time radon concentrations with measured concentrations. The model was shown to be a reliable tool for such predictions. The key variables with respect to radon mitigation were the ventilation rate, k_v, differential pressure between the subslab and basement, ΔP, and the foundation flow resistance, I_f. Based on the verified relationship, one can conclude that indoor radon levels can be decreased by increasing k_v, increasing I_f (therefore properly sealing the foundation), and decreasing ΔP (therefore using an ASD system). It was also shown in this study that a proper analysis of measured radon concentrations can be used to discover a leak in the ASD system.

6.6 References

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c_dot = -(k_v+k+k_d)*c + k_v*p*c_a + s;

s = deltaP*c_s/(V*l_f)

k_v	- ventilation rate
k	- decay rate
k_d	- deposition rate
c	- indoor pollutant concentration
p	- penetration factor
c_a	- ambient pollutant concentration
s	- indoor source strength
deltaP	- pressure difference subslab-basement
c_s	- subsurface radon concentration
V	- basement volume
l_f	- foundation flow resistance
c_0	- initial indoor pollutant concentration

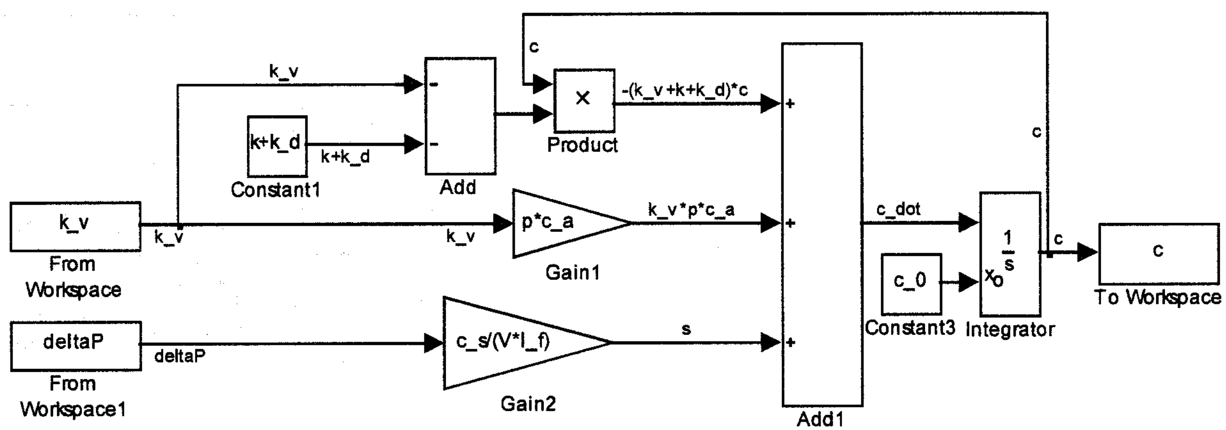

Figure 6.1 Simulink® model with the ventilation rate and differential pressure as the inputs and the indoor radon concentration as the output

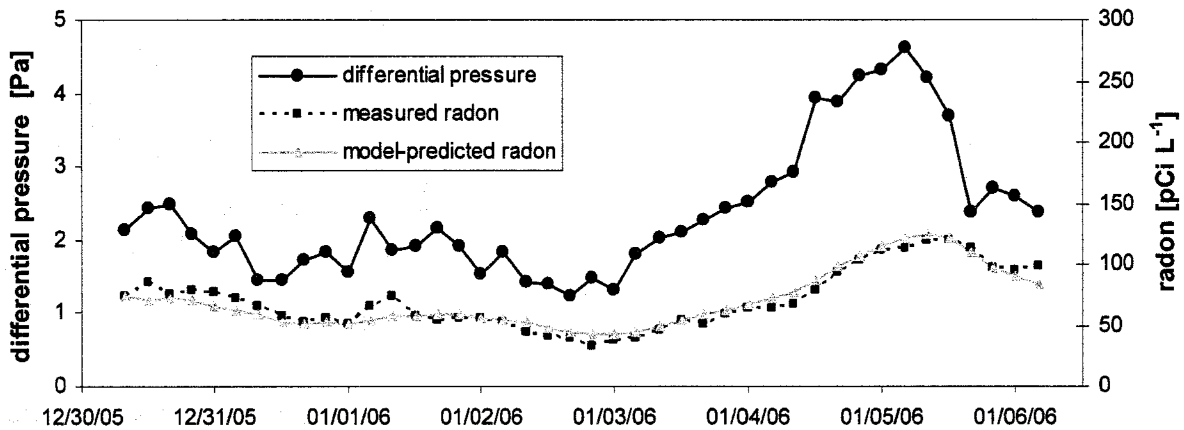

Figure 6.2 Differential pressure between the subslab and basement (left y-axis); measured and model-predicted basement radon concentration (right y-axis)

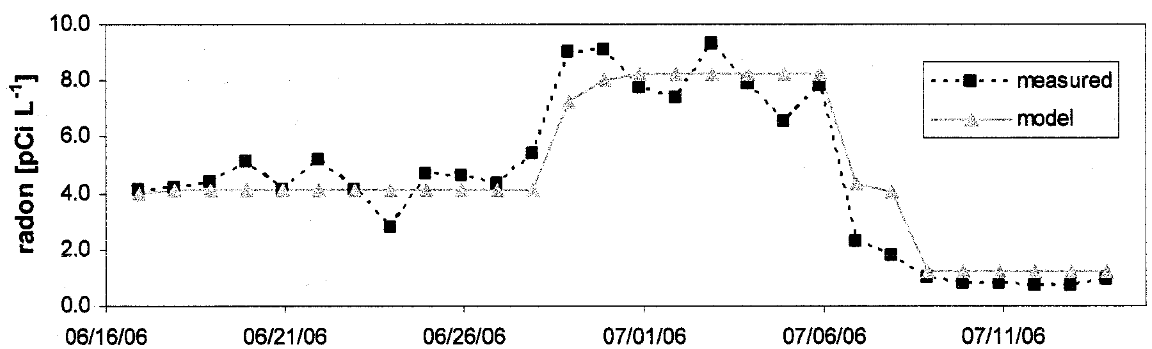

Figure 6.3 Measured basement radon concentration and concentration predicted by the model based on the log of HRV settings

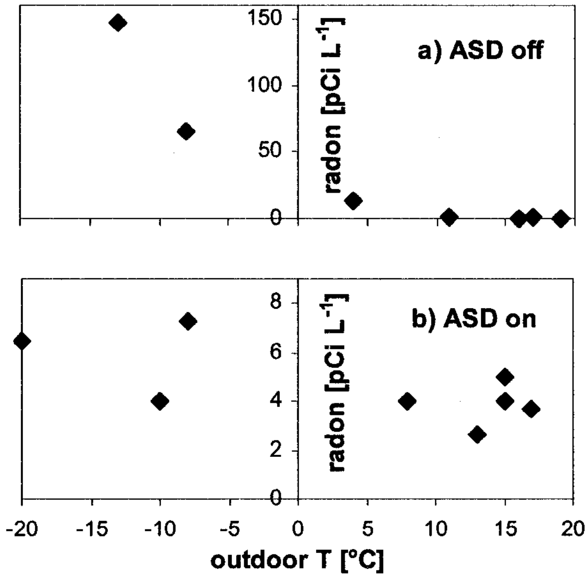

Figure 6.4 Basement radon concentration as a function of outdoor temperature with a) ASD "off", b) ASD "on"

Chapter 7
General Results and Discussion

The main results of this thesis are presented and discussed in the individual papers. Not all results were presented because of space limitations. The extended set of results of the $PM_{2.5}$ and CO measurements, including the results of the state-space model analysis (including both data already presented in the paper and data not presented), is presented in the appendix. Table A-1 shows the summary of $PM_{2.5}$ results for all studied buildings. Figures A-1 to A-8 show the real-time outdoor, indoor, and model-predicted $PM_{2.5}$ concentrations for all measurement periods for which the state-space model analysis method was used. Table A-2 shows the summary of CO results for all studied buildings. Figures A-9 and A-10 show the real-time outdoor, indoor, and model-predicted CO concentrations for all measurement periods for which the state-space model analysis method was used.

The following sections summarize and discuss the results that were not included in the papers because of space limitations, but that are still worth presenting in this thesis.

7.1 $PM_{2.5}$ Results

The outdoor $PM_{2.5}$ data from the UAF Duckering building in the period from 12/15/06 to 12/20/06 was compared with the downtown data for the same period collected at the permanent monitoring station. While the average at UAF was 3.8 $\mu g/m^3$ (see Table A-1), it was 24.2 $\mu g/m^3$ in the downtown area. This suggests that the $PM_{2.5}$ pollution problems are mainly around the downtown area. But, a more extensive $PM_{2.5}$ spatial distribution study needs to be performed to be able to draw more certain conclusions.

The average outdoor $PM_{2.5}$ level on Chena Ridge (Ellesmere Dr) in the winter period from 12/30/05 to 1/6/06 was 0.6 $\mu g/m^3$ (see Table A-1), therefore practically zero. The downtown average for the same period was 49.4 $\mu g/m^3$. This supports the theory that, in the wintertime, pollutants are mainly trapped below the inversion layer and higher locations do not, in general, have air pollution problems (there can be problems where wood stoves see heavy use).

The average indoor $PM_{2.5}$ levels during the fall and winter at the three Fairbanks residences studied varied from 1.6 to 6 $\mu g/m^3$. The levels increased to 23.2 $\mu g/m^3$ during the summer at one of these residences (some smoke from forest fires during this period). Ramachandran et al. [1] found the average indoor $PM_{2.5}$ gravimetric concentration to be 13.9 $\mu g/m^3$ in a study of 30 residences in 3 communities in Minnesota over the spring, summer, and fall seasons. Johnson et al [2] found a wintertime average of 18.0 $\mu g/m^3$ at one home in Fairbanks and a summertime of 12.0 $\mu g/m^3$ (without influence of forest fires) at another house each over a period of several days.

In a study of 178 non-smoking homes in Riverside, California, Ozkaynak et al [3] found median residential indoor $PM_{2.5}$ to be 34 and 26 $\mu g/m^3$ during the day and night, respectively. The corresponding ambient levels were 36 and 35 $\mu g/m^3$, respectively. According to the US EPA [4], the average annual $PM_{2.5}$ levels at 750 sites in the US decreased from 14 to about 12 $\mu g/m^3$ from 1999 to 2006.

7.2 CO Results

Attached-garage CO levels were measured at all three residential buildings. This was done during the winter measurement periods. As seen in Table A-2, the garage CO level is significantly higher than the indoor level in all three cases. While the average level for the three measurements is 0.5 ppm indoors, it is 4.1 ppm in the garages. The maximum 10-min average CO level measured in a garage was 121 ppm. Even though people spend a minimum of their time in garages, the elevated levels are still of concern because the CO can penetrate into the houses.

Only at one of these residential buildings (Jack St), the outdoor CO level was accurately measured. The average CO level was 0.39 ppm outdoors, while it was 0.91 indoors, therefore 0.52 ppm higher. No other indoor CO sources are known besides the attached garage. Therefore, it can be concluded that the attached garage was responsible for the increase of about 0.5 ppm in the indoor CO levels. Graham et al. [5] found the instantaneous in-house CO level as high as 32.5 ppm after a cold vehicle start in an attached garage.

As seen in Table A-2, the average indoor CO level at the Courthouse Square building was 0.85 ppm, while the average outdoor level was 1.05 ppm. This may seem to contradict the expectation that the average indoor CO level in the absence of indoor sources approximately equals the outdoor level due to the relatively high chemical stability of CO. However, the outdoor measurement was performed at the corner of the building as mentioned in Chapter 2. The corner is at an intersection, and therefore, the levels measured at that location are not representative of the levels penetrating into the building. Those levels are expected to be lower.

Wallace [6] found average 1-hr CO levels to range from about 0.15 to 0.85 ppm at an occupied townhouse in Virginia for the month of January 1998 with peaks around 8 AM and 5 PM. Each if these values represent the average of the given hours over 31 days. According to the US EPA [7], the average of the annual 2nd highest 8-hr ambient CO at 144 sites in the US decreased from 9 to 3 ppm between 1980 and 2006.

7.3 Particle Count Results

The smallest particle size detectable by the used particle counters is 0.3 μm. The peak of the particle-size mass-distribution of the typical urban $PM_{2.5}$ is between 0.3 and 0.4 μm [8]. It means that a significant part of $PM_{2.5}$ was probably undetected by the particle counters used in our study. They were used for the estimates of penetration factors in the available size ranges above 0.3 μm. However, a side-by-side test showed a discrepancy between the measurements of the two particle counters. Therefore, no accurate data regarding the penetration of particles of various sizes was obtained.

7.4 PAH Results

For most of the deployment periods, the measured average outdoor and indoor levels were below the lower threshold of 10 ng/m^3 specified by the manufacturer. Despite the low average levels, spikes in indoor concentrations were observed at residential buildings with the highest 10-min average value of 984 ng/m^3. These spikes were attributed to indoor sources as no cause was seen in the outdoor levels. The specific indoor activity was not determined though.

Only two deployments resulted in average PAH levels exceeding 10 ng/m^3. At the FNSB transportation building, the average outdoor level was 25.6 ng/m^3 and the average indoor level was 18.4 ng/m^3, resulting in an I/O ratio of 0.72. At the Courthouse Square building, the average outdoor level was 23.7 ng/m^3, and the average indoor level was 12.5 ng/m^3, resulting in the I/O ratio of 0.53. These two deployments were also those with the highest outdoor $PM_{2.5}$ levels, excluding the deployments during wild-fire smoke. This suggests an association between the $PM_{2.5}$ and PAH levels. However, no significantly elevated PAH levels were observed during wild-fire smoke. The PAH I/O ratios of 0.72 and 0.53 mentioned earlier are higher than the $PM_{2.5}$ ratios of 0.38 and 0.19 found for the same two buildings, respectively. This suggests that a higher proportion of PAHs is attached to the particles in the size region with higher penetration efficiency. This may be associated with the particle-size surface-area-distribution, which typically peaks around 0.2 μm [2]. This is around the particle size where efficiencies of filters reach their minimum [2].

At six different non transportation indoor microenvironments in Boston such as a library, a food court, and a hospital, Levy et al. [9] found the mean PAH levels ranged from 5 to 12 ng/m^3. The 10 minute values ranged from about 2 to 40 ng/m^3.

7.5 Elemental Carbon Results

It was found that the outdoor levels of elemental carbon (EC) generally correlate with the outdoor $PM_{2.5}$ levels. However, no exact evaluation was done because, as mentioned earlier, the Aethalometer was not collocated with the other instruments. Also, the effect on the indoor levels was not studied because only one Aethalometer was available. The outdoor average levels (measured at the UAF Energy Center) ranged from 470 to 1180 ng/m^3.

LaRosa et al. [10] collected 10 months of data at a home in northern Virginia in 1999 and 2000 and found a mean EC of 680 ng/m^3, 99% less than 2,929 ng/m^3 for ambient air. The average indoor to outdoor ratio was 0.35, with the strongest indoor source being the burning of citronella candles. They reported median EC levels in ambient air in the US were 700 ng/m^3 in 24 rural areas and 1,400 ng/m^3 in 15 urban areas. Although considered inert, materials found to coat EC have been found to be mutagenic and carcinogenic.

7.6 TVOC Results

An extensive TVOC research was beyond the scope of our study. Presented results are based on the "walk-through" with the VOC Monitor. The TVOC concentrations inside all buildings (excluding measurements in garages) were in the range from 90 to 340 ppb, except for the house on Ellesmere Drive. This was a totally new house (finished in May 2005), and the indoor TVOC concentrations were 1200 ppb in July 2005 and 490 ppb in January 2006. This is probably associated with the outgassing of the new materials.

The garage TVOC levels were usually higher than the levels in the living portions of the houses. This was most noticeable at the FNSB transportation building where the TVOC levels in the office area were 260 ppb, while they were 4000 ppb in the garage/workshop area. This suggests that VOCs can have similar issues as CO, with respect to penetration from attached garages into the remaining areas of buildings, as discussed in section 7.2.

In a prior study in Fairbanks [2], the TVOC levels in homes were normally < 300 ppb (as isobutylene) measured by the handheld VOC Monitor. Baking bread elevated these levels to 600 ppb in the kitchen of house no. 2 (electric oven with no exhaust fan). Normal indoor air has a TVOC level of 100-400 ppb Isobutylene Units [11]. Wallace [12] found about half of 750 homes sampled in the US had TVOC levels greater than 1000 $\mu g/m^3$.

Building materials and consumer products like air fresheners are major VOC sources in non-smoking homes.

7.7 Organic Vapor Results

These results are based on the time-averaged levels measured using the Organic Vapor Diffusion Monitors. The indoor levels in all measured buildings, excluding garages, were below 3 ppb for benzene, 4 ppb for n-hexane, and 8 ppb for toluene, with the exception of the measurement in the house on Ellesmere Drive in July 2005 where the levels were 23 ppb for benzene, 22 ppb for n-Hexane, and 37 ppb for toluene. These higher levels may be associated with the wild-fire smoke because this was the only measurement with Organic Vapor Diffusion Monitors during wild-fire smoke.

The levels in garages were higher than the levels in living portions of the buildings. The highest garage levels were found in the house on Ellesmere Drive in December 2005, where the levels were 38 ppb for benzene, 44 ppb for n-Hexane, and 71 ppb for toluene.

In Johnson et al. [2], benzene and n-hexane levels were less than 10 $\mu g/m^3$ (~ 3 ppb) and toluene less than 18 $\mu g/m^3$ (~ 5 ppb) for two homes in Fairbanks. In a study in Valdez, Alaska involving 58 homes, benzene levels averaged 16 and 25 $\mu g/m^3$, respectively, in the summer and winter [12]. Isbell et al. [13] found 12 hour benzene and toluene levels ranged from 1 to 39 and 1 to 104 ppb respectively in the living areas of two subarctic homes with attached garages. These data included summer and winter seasons. In the garages, the benzene and toluene levels were as high as 304 and 638 ppb, respectively.

7.8 Formaldehyde Results

The Formaldehyde Diffusion Monitors were used only at two locations. In winter 2005-2006, the formaldehyde level in the house on Jack Street was 40 ppb, while it was 96 ppb in the house on Ellesmere Drive. The level in the house on Ellesmere drive in summer 2005 was 180 ppb. The trend of these results agrees with the trend of the TVOC results discussed in section 7.6. The house on the Ellesmere Drive is a totally new house, and the elevated formaldehyde levels are probably associated with the outgassing of the new materials. The extent of the outgassing decreases with time.

According to Goodish [14], most residential buildings in the US and Canada have formaldehyde levels less than 100 ppb with levels in offices commonly between 20 and 40 ppb.

7.9 References

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Chapter 8
General Conclusions

Several computer models were developed that allow for studying the effect of outdoor air quality on indoor air. Outdoor and indoor air quality was measured at several buildings in Fairbanks, Alaska, and the developed models were used to quantify the effect of outdoor pollutant levels on the levels indoors, and to estimate the indoor levels in other scenarios with respect to ventilation rate and other factors. The study was focused on $PM_{2.5}$, CO, and radon, but also other pollutants were examined to a lesser extent. The following sections summarize the main conclusions.

8.1 Computational Modeling

Conclusions of this thesis regarding computational modeling and its use in air quality studies are summarized in the following points:

- MATLAB® is a suitable platform for implementing models of the dynamic relationship between the ambient and indoor pollutant concentrations. The Control System Toolbox® is convenient for modeling the scenarios where the air exchange rate and other parameters are constant, due to its support of the state- space models. MATLAB® Simulink® is a suitable platform for implementing the models of more complex scenarios where the air exchange rate or other parameters vary with time.

- For the scenarios with constant model parameters, it is possible to estimate the model parameters only based on the real-time measured indoor and outdoor pollutant concentrations, using the state-space model identification method (described in Chapter 3). In order to determine the model parameters, it is not necessary to explicitly measure related parameters, such as the ventilation or deposition rates.

- If indoor pollution sources are limited and the model parameters are known, the real-time indoor pollutant levels can be accurately predicted based on the real-time outdoor levels.

- A dynamic model can be used to estimate the as-installed HVAC filter efficiency based on the real-time values of the indoor and outdoor $PM_{2.5}$ levels, and the HVAC variables.

- The good agreement between model-predicted and measured indoor pollutant concentrations shown in this study implies that predictions related to indoor air quality can be made in the design stage of a building and its ventilation system. These predictions can be used to move closer toward optimizing the design with respect to indoor air quality, energy efficiency, economy, environmental impact, and other aspects.

8.2 Fine Particulate Matter

Conclusions of this thesis related to both Fairbanks $PM_{2.5}$ and general $PM_{2.5}$ findings are summarized in the following points:

- During elevated levels of outdoor $PM_{2.5}$, the indoor $PM_{2.5}$ level in residences can be dominated by particles of outdoor origin rather than particles from indoor sources. In our study of the residences in Fairbanks, the outdoor generated $PM_{2.5}$ was responsible in average for about 67% of the indoor $PM_{2.5}$.

- During elevated levels of outdoor $PM_{2.5}$, the indoor $PM_{2.5}$ levels in commercial buildings caused by indoor sources can be negligible with respect to the levels caused by particles of outdoor origin. In our study in Fairbanks, the outdoor generated $PM_{2.5}$ was responsible for more than 97% of the indoor $PM_{2.5}$ at each of the four studied commercial buildings.

- The indoor exposure to particles of outdoor origin is not negligible with respect to the exposure outdoors. The effective penetration efficiency for $PM_{2.5}$ at the studied buildings in Fairbanks ranged from 0.16 to 0.69.

- The results of our study imply that reducing outdoor $PM_{2.5}$ levels can have significant health benefits even for people spending most of their time indoors.

- The indoor $PM_{2.5}$ level can be significantly decreased by using a smart ventilation control algorithm that takes indoor and outdoor $PM_{2.5}$ levels into account. The HVAC control algorithm developed in our study for a commercial building in Fairbanks was shown to reduce the indoor levels by 65%.

- Results for one commercial building in Fairbanks suggest that improperly sealed HVAC filters can have a strong negative impact on the filtering efficiency.

- Using an HRV with an additional filter was found to be the best solution for the ventilation of a typical Fairbanks home with respect to consumed energy, indoor air quality, overall economy, and environmental impact. Ventilation using an HRV was shown to save about 380 USD annually in the energy costs compared to using natural ventilation. Using an HRV with an additional filter was shown to save about 690 USD annually in the health damage cost associated with breathing indoor $PM_{2.5}$ compared to using natural ventilation, even though uncertainties exist in the evaluation of the health damage cost.

- Two main strategies can be used to reduce human exposure to $PM_{2.5}$ of outdoor origin: a) reducing outdoor $PM_{2.5}$ levels and b) improving ventilation systems. In Fairbanks, the outdoor $PM_{2.5}$ levels can not be completely eliminated because they are partly caused by natural sources (wild fires). Similarly, the exposure to outdoor $PM_{2.5}$ can not be completely eliminated by improved ventilation because people still need to spend some of their time outdoors. Therefore, the most effective solution is the combination of both strategies.

8.3 Carbon Monoxide

Conclusions of this thesis related to both Fairbanks CO and general CO findings are summarized in the following points:

- The effective penetration efficiency for CO is close to unity. This implies that a building doesn't protect users from exposure to the outdoor average CO levels and the only practical way to reduce this exposure is to reduce the outdoor CO levels.

- The average indoor CO levels in residences are generally higher than outdoor levels because of the presence of indoor sources.

- Attached garages were shown to be a potential significant source of indoor CO. The time-averaged garage CO at a Fairbanks house was found to be 4.9 ppm higher than the outdoor CO and it was increasing the CO level in the living portion of the house by 0.5 ppm. Attached garages should be designed in such a way that the penetration of pollutants into living portions is limited.

- The maximum 10-minute CO levels at the 7 buildings we studied were well below the 8-hour NAAQS standard of 9 ppm.

8.4 Radon

Conclusions of this thesis related to both Fairbanks radon and general radon findings are summarized in the following points:

- Buildings in hilly areas around Fairbanks can have elevated indoor radon concentrations.

- Indoor radon concentrations can be decreased by implementing the following measures: increasing the ventilation rate, decreasing the differential pressure between the subslab and house interior (by means of a subslab depressurization system), and increasing the flow resistance of the foundation (by properly sealing it during construction). The effect of these measures can be reliably predicted by means of the model developed in this study.

- An improperly installed subslab depressurization system can result in the increase of the indoor radon levels rather than their decrease. This study demonstrated that a leak in such a system can be discovered by proper analysis of measured radon concentrations.

8.5 Other Conclusions

- PAHs may have higher effective penetration efficiencies than $PM_{2.5}$. This can be caused by the relatively large surface area of particles in the size region around 0.2 μm, which is around the particle size where efficiencies of filters reach their minimum.

- The indoor PAH levels we observed were in the range of what others have found for indoor microenvironments.

- New buildings can have higher VOC levels due to outgassing of the new materials.

- VOC levels in garages are usually higher than in the living portions of buildings. This may result in issues similar to those with CO. If garages are attached to buildings, the VOCs can penetrate indoors. Attached garages should be designed in such a way that the penetration of pollutants into the living portions of buildings is limited.

- With the exception of the initial period for a brand new house, the TVOC levels in the living parts of the three residences were in the lower 50 % compared with one study involving 750 homes in the contiguous US.

- The average indoor $PM_{2.5}$ levels at the three residences we studied were comparable to the levels others have found for US homes.

- For the 12 data sets analyzed, with one exception, the maximum indoor 10-minute $PM_{2.5}$ levels were less than the maximum outdoor levels. In all cases, the average levels were below the 24-hour NAAQS of 35 $\mu g/m^3$.

- The formaldehyde levels in a new house we studied decreased by about a factor of two after six months of occupancy.

8.6 Recommendations for Future Work

- The state-space model identification method developed in this study is usable for scenarios where the ventilation rate and other parameters are constant with time. A similar model identification method could be developed for scenarios where the ventilation rate varies with time. This method could be used for buildings with mechanical ventilation systems (such as residences with HRVs) where the ventilation rate as a function of time is known. The ventilation rate and the measured indoor and outdoor pollutant concentrations would be the inputs for this method. This method would allow for analyzing longer data sets. The use of the current method was limited to sections where the ventilation rate was constant.

- The model identification method could be further extended into a more complex method that would allow for analyzing scenarios with recirculated air. The basic principle would be the same, but this complex method would probably require an iterative algorithm because generally all parameters in the model with recirculated air affect the correlation between the measured and model-predicted indoor concentration, unlike the model with no recirculation, where the penetration factor is only a scaling factor with no effect on the mentioned correlation.

- An energy-air-quality model of a residence with an indoor air cleaner could be developed. This model would be similar to the model developed in this study for HRV-equipped residences, which also includes the scenario of recirculating the indoor air. More research would have to be done on the energy and economical aspects of available indoor air cleaners.

- Only very limited data was obtained in this study with regard to the penetration of pollutants (here CO and VOCs) from attached garages into living portions of buildings. Performing a more extensive study in this area would be beneficial for human health.

- With regard to studying the effect of outdoor air quality on indoor air, more extensive research could be done regarding particle size distribution, PAHs, and VOCs.

- Very little is known about the spatial distribution of $PM_{2.5}$ in Fairbanks. Our study suggests that the winter $PM_{2.5}$ levels in areas farther from the downtown are much lower than those measured at the permanent monitoring station located downtown. More extensive research on the $PM_{2.5}$ spatial distribution should be done because $PM_{2.5}$ is the pollutant of serious concern in Fairbanks. Based on past $PM_{2.5}$ data, Fairbanks will likely become a non-attainment area with respect to the new 24-hour US EPA $PM_{2.5}$ standard.

- As concluded earlier, the outdoor $PM_{2.5}$ levels can have significant health effects even on people who spend the majority of their time indoors. Therefore, reducing the outdoor $PM_{2.5}$ levels is of a great importance. However, little is known about the relative importance of sources of outdoor $PM_{2.5}$ in Fairbanks during the winter. Extensive research in this area needs to be done. Identifying major sources is the first step in reducing the outdoor $PM_{2.5}$ levels.

8.7 Summary of Main Contributions of this Thesis

- A state-space model analysis method was developed (see Chapter 3) to quantify the effect of outdoor air quality on indoor air based on measured real-time outdoor and indoor pollutant concentrations. To the best of our knowledge, this is the first time that this method was used in the area of air quality. Methods used by others require steady-state conditions or long-term averages for their analysis. This results in very long measurement periods in order to obtain a sufficient amount of samples. Our method uses a dynamic model and allows the use of transient samples for the analysis, which allows for acquiring a sufficient amount of samples in a relatively short measurement period. Thanks to the unique algorithm of the analysis method, it doesn't require the explicit knowledge of the state space model parameters; they are determined from the measured real-time pollutant concentrations.

- The knowledge base related to the effect of outdoor air quality on indoor air (especially with respect to $PM_{2.5}$), although well represented in the literature, is still incomplete. This is partly due to the difficulties of conventional analysis methods that require tedious measurements over extensive periods of time. Our work has contributed to this knowledge base by quantifying the effect of outdoor air quality on indoor air at several buildings in Fairbanks. Our results support the conclusions of others that outdoor air quality has a significant effect even on people spending most of their time indoors. This strengthens the argument for decreasing the outdoor air pollution.

- A $PM_{2.5}$ control strategy for an HVAC system was presented in this thesis (see Chapter 4) which takes into account both the outdoor and indoor $PM_{2.5}$ levels. To the best of our knowledge, this is the first time that such a control strategy is presented. A control strategy for CO was presented by other authors; however, the approach for $PM_{2.5}$ control is different in that $PM_{2.5}$ (unlike CO) is affected by filters. Other authors presented a control strategy for particulates in cleanrooms that only takes indoor particulate levels into account; this strategy wouldn't be suitable for office buildings. Our control strategy is designed for office buildings and takes both indoor and outdoor $PM_{2.5}$ into account. It was shown to significantly reduce indoor $PM_{2.5}$ levels.

- A model of an HRV-equipped residence was developed (see Chapter 5) to evaluate the building's performance from the perspective of energy and air quality. It was used to evaluate several ventilation scenarios of a typical home in Fairbanks. The scenarios were compared based on the total yearly costs which included the external costs associated with breathing the indoor $PM_{2.5}$. To the best of our knowledge, this is the first time that such a comparison was made. This can benefit those that plan to build a new home or reconstruct an old one.

- Our results are being conveyed to the Fairbanks North Star Borough. Our results emphasize the importance of decreasing the outdoor $PM_{2.5}$ and our suggestions for future work include quantifying the outdoor $PM_{2.5}$ sources in Fairbanks, which is the first step in decreasing the outdoor $PM_{2.5}$ levels.

- The ultimate contribution of this thesis is that it benefits public health. This is done via providing the evidence of the effects of outdoor air-quality and thus supporting the pressure to maintain clean outdoor air. It is also done via providing the information on ventilation techniques that enhance indoor air quality.

Appendix

Tables and Graphs Summarizing the Results for $PM_{2.5}$ and CO at Studied Buildings

Table A-1 Summary of the $PM_{2.5}$ results of the outdoor/indoor study

Bldg	Mech. Vent.	Analyzed period	Outdoor $PM_{2.5}$ [µg/m3]			Indoor $PM_{2.5}$ [µg/m3]			I/O ratio	P**	Indoor $PM_{2.5}$ [µg/m3]***	
			avg	min*	max*	avg	min*	max*			From outdoors	From indoor sources
Residential:												
Ellesmere Dr	yes	6/22/05 - 7/12/05	24.4	2.0	123.0	23.2	5.0	83.0	0.95	0.69	16.8	6.4
		12/30/05 - 1/6/06	0.6	0.0	23.0	1.6	0.0	7.0	2.70	-	-	-
Jack St	no	10/3/05 - 10/17/05	6.4	1.0	103.0	1.6	1.0	30.0	0.25	0.18	1.2	0.4
		2/15/06 - 2/27/06	10.8	1.0	119.0	2.5	1.0	154.0	0.23	0.19	2.1	0.4
Hamilton Acr	no	11/16/05 - 11/30/05	14.7	2.0	300.0	6.0	1.0	155.0	0.41	0.16	2.4	3.6
Commercial:												
UAF Duck	yes	7/21/05 - 7/23/05	16.0	1.0	55.0	10.4	1.0	36.0	0.65	0.69	11.0	-0.6
		3/3/06 - 3/16/06	8.2	2.2	24.8	2.0	0.6	4.3	0.24	-	-	-
		8/23/06 - 9/5/06	2.2	0.0	33.0	0.9	0.0	17.0	0.42	-	-	-
		12/15/06 - 12/20/06	3.8	0.0	17.7	1.4	0.0	6.2	0.38	-	-	-
FNSB Transport	yes	12/9/05 - 12/19/05	20.2	2.0	96.1	7.7	2.0	26.5	0.38	0.37	7.5	0.2
Courthouse Sq	yes	1/27/06 - 2/7/06	27.0	0.0	112.0	5.1	0.0	20.0	0.19	0.21	5.7	-0.6
CCHRC RTF	yes	2/16/07 - 2/20/07	7.6	3.4	20.3	1.8	1.0	5.5	0.24	0.23	1.7	0.1

* Minimum and maximum levels are based on 10-min average values
** Effective penetration efficiency as determined by the state-space model analysis method
*** Components of the indoor $PM_{2.5}$ calculated from the measured outdoor concentration and the effective penetration efficiency

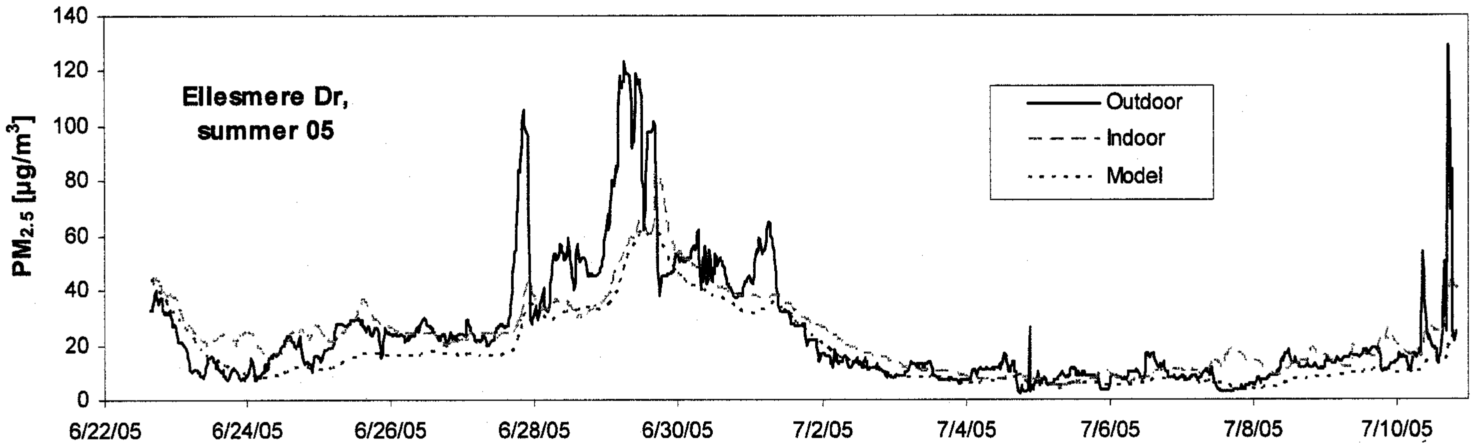

Figure A-1 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the residential building on Ellesmere Dr in summer 05

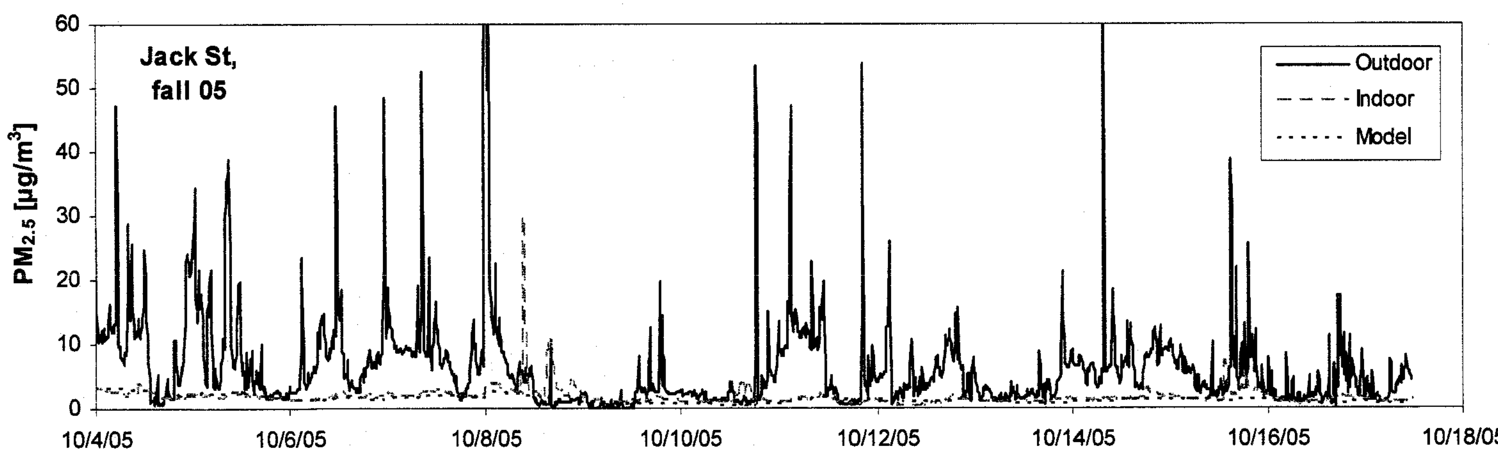

Figure A-2 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the residential building on Jack St in fall 05

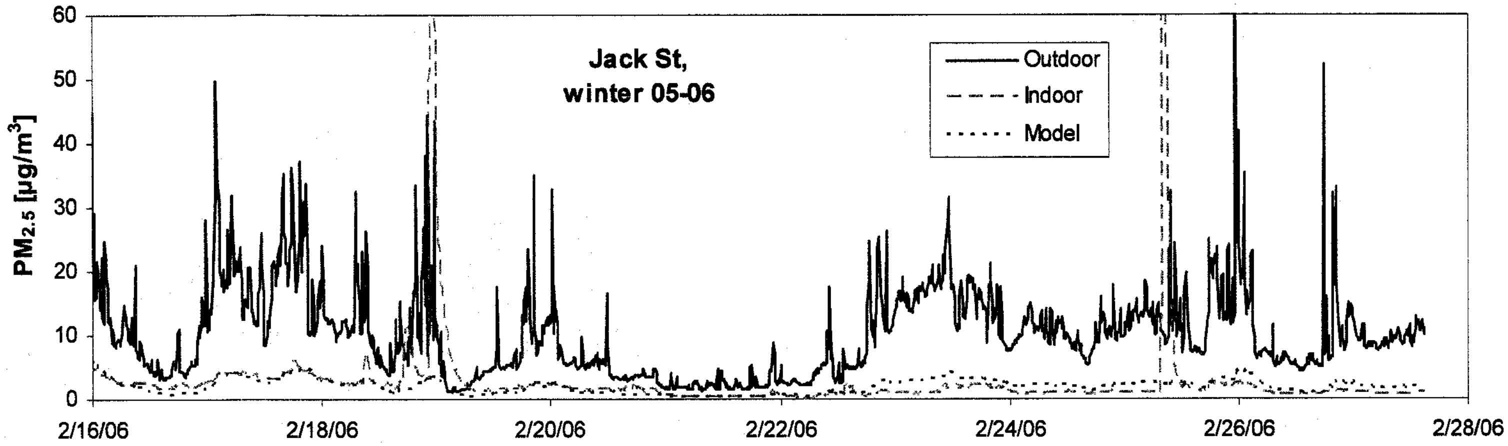

Figure A-3 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the residential building on Jack St in winter 05-06

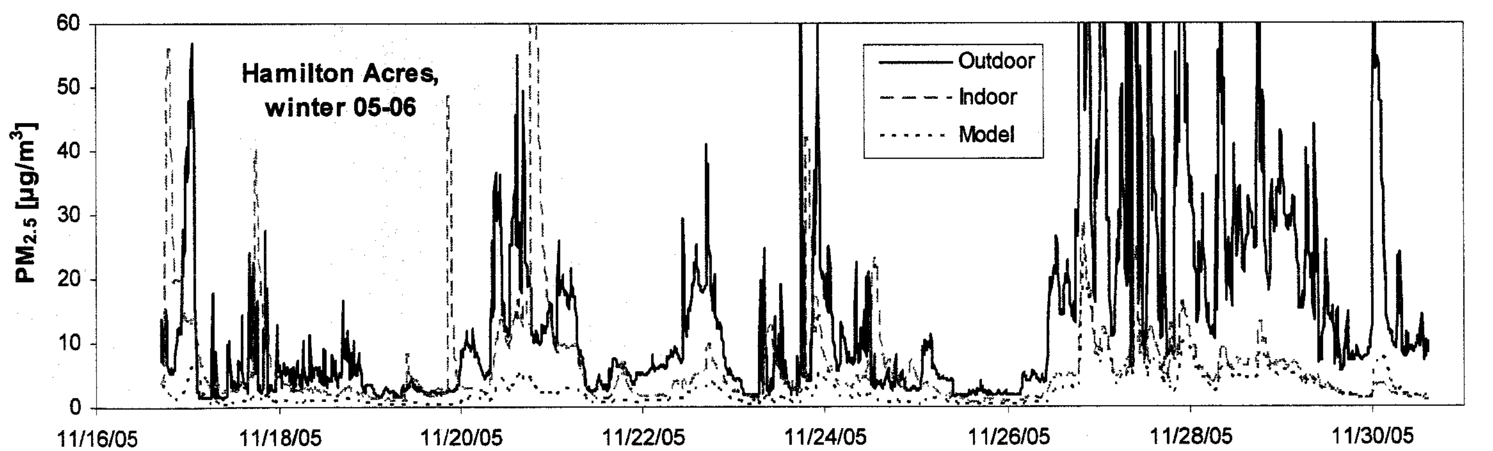

Figure A-4 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the residential building in Hamilton Acres in winter 05-06

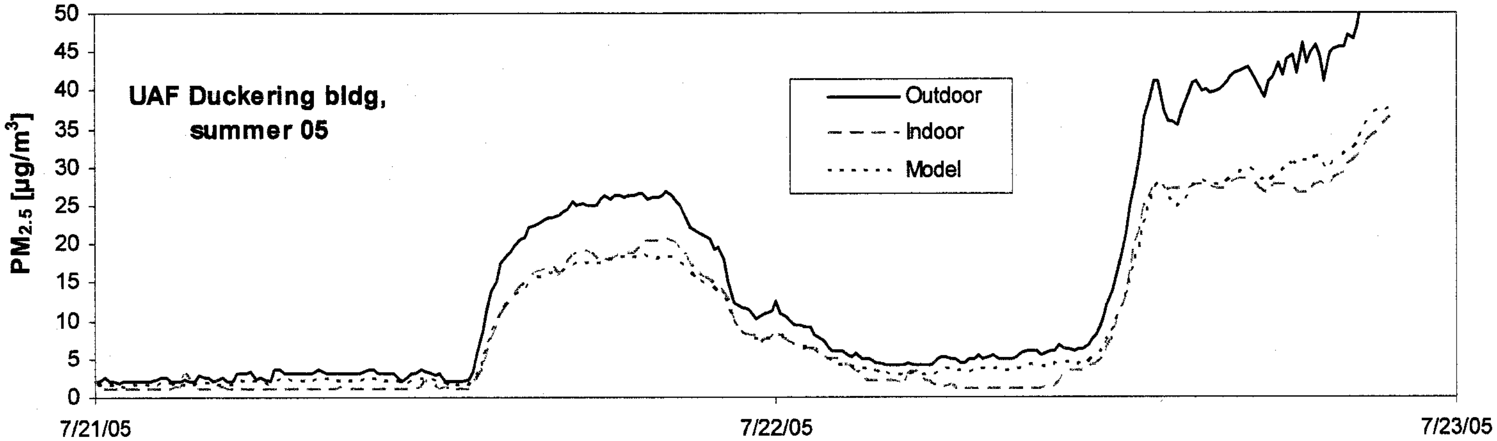

Figure A-5 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the UAF Duckering building in summer 05

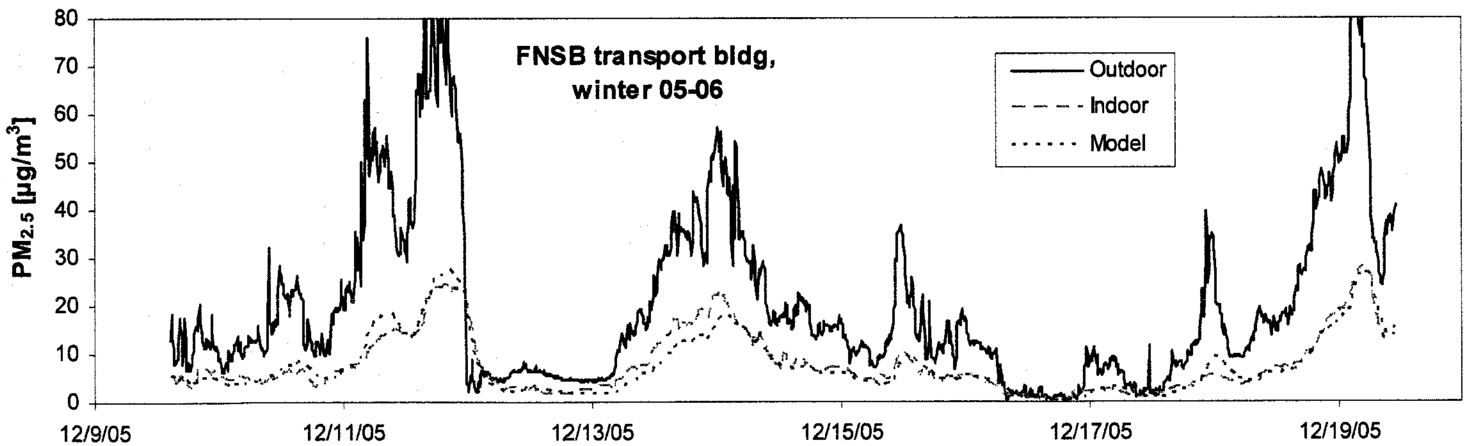

Figure A-6 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the FNSB transportation department building in winter 05-06

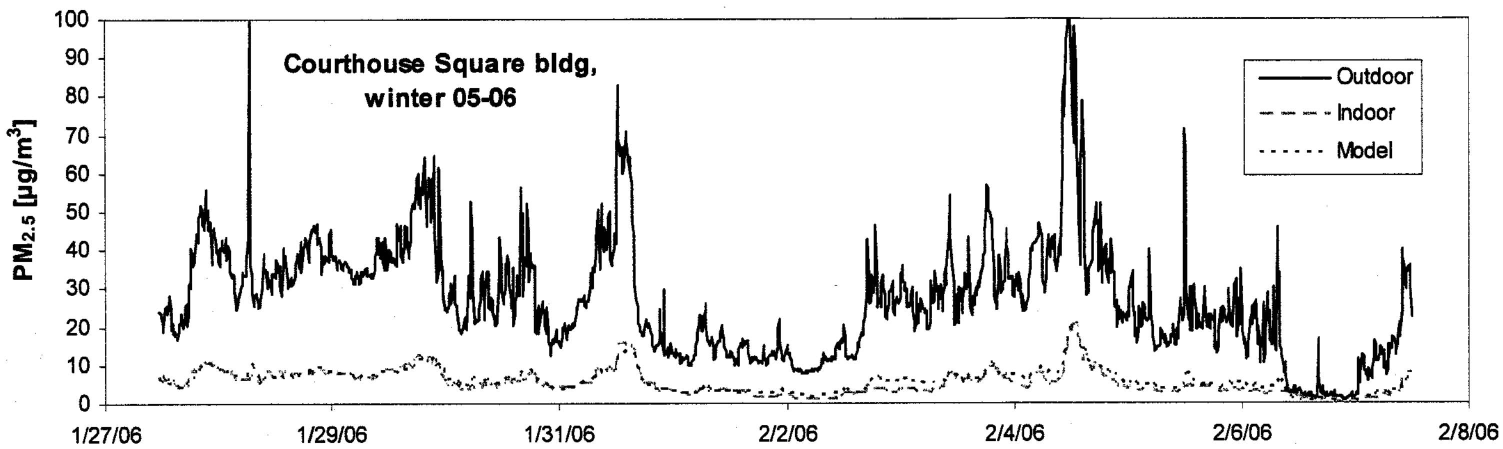

Figure A-7 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the Courthouse Square building in winter 05-06

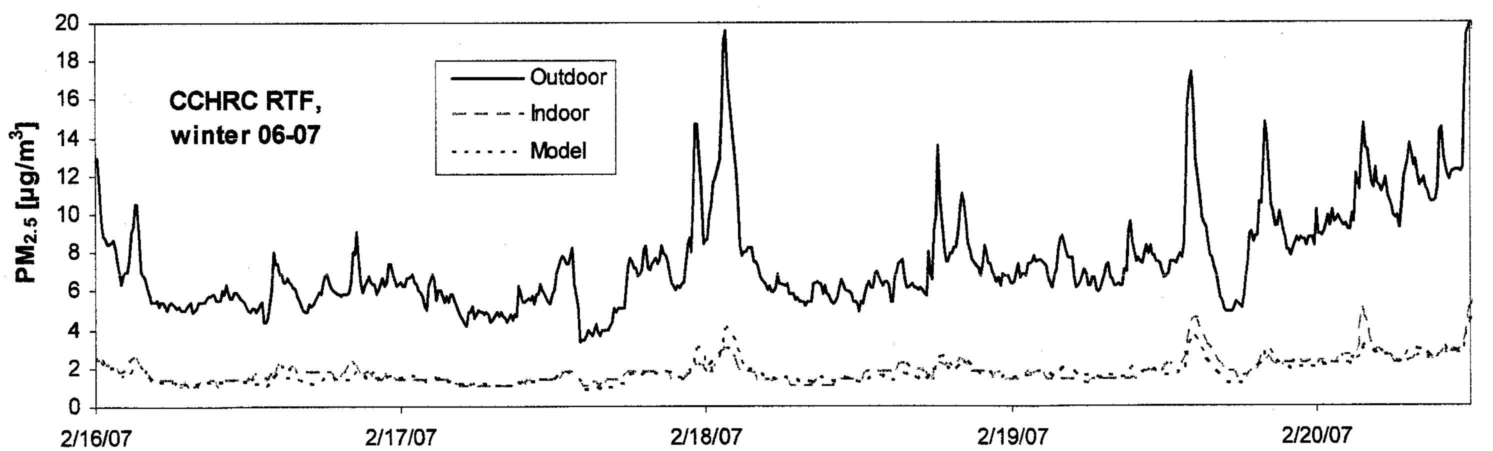

Figure A-8 Measured outdoor and indoor $PM_{2.5}$ concentration, and the state-space model output at the CCHRC RTF building in winter 06-07

Table A-2 Summary of the CO results of the outdoor/indoor study

Bldg	Mech. Vent.	Analyzed period	Outdoor CO [ppm]			Indoor CO [ppm]			Garage CO [ppm]			I/O ratio	P**
			avg	min*	max*	avg	min*	max*	avg	min	max		
Residential:													
Ellesmere Dr	yes	12/30/05 - 1/12/06	-	-	-	0.17	0.05	0.80	1.21	0.00	69.00	-	-
Jack St	no	10/3/05 - 10/17/05	-	-	-	0.58	0.05	3.57	-	-	-	-	-
		2/15/06 - 2/27/06	0.39	0.05	2.00	0.91	0.20	2.40	5.30	0.00	87.00	2.33	-
Hamilton Acr	no	11/16/05 - 11/30/05	-	-	-	0.43	0.00	1.40	5.74	0.00	121.00	-	-
Commercial:													
UAF Brooks	yes	3/3/06 - 3/16/06	0.26	0.10	1.15	0.28	0.13	0.96	-	-	-	1.08	1.07
		12/8/06 - 12/22/06	0.36	0.08	1.33	0.41	0.10	1.16	-	-	-	1.12	0.99
FNSB Transport	yes	12/9/05 - 12/19/05	-	-	-	0.87	0.05	2.33	-	-	-	-	-
Courthouse Sq	yes	1/24/06 - 2/7/06	1.05	0.23	3.78	0.85	0.06	2.99	-	-	-	0.81	-
CCHRC RTF	yes	2/16/07 - 2/20/07	0.32	0.09	1.87	0.39	0.15	2.75	-	-	-	-	-

* Minimum and maximum levels are based on 10-min average values
** Effective penetration efficiency as determined by the state-space model analysis method

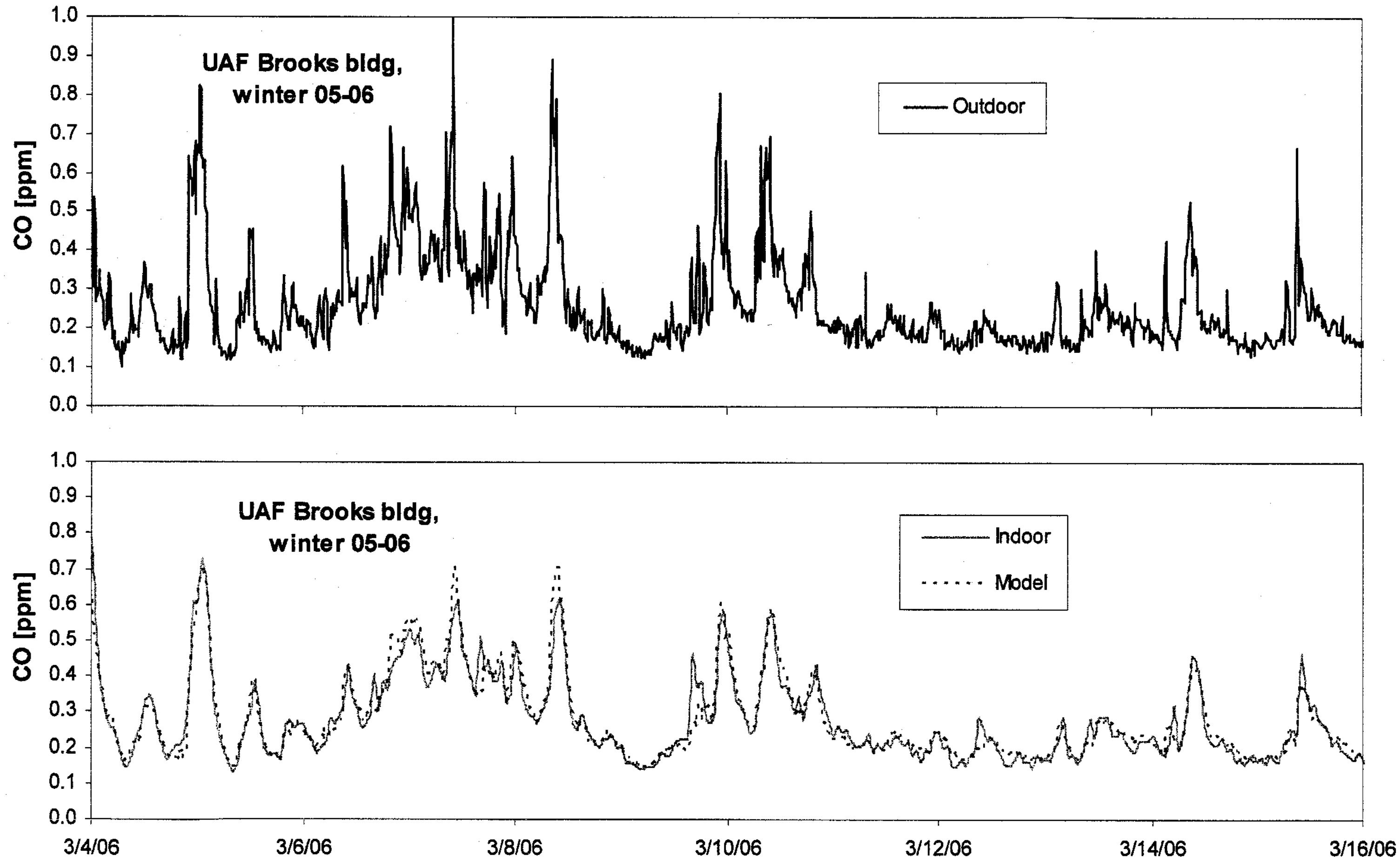

Figure A-9 Measured outdoor and indoor CO, and the state-space model output at UAF Brooks bldg in winter 05-06

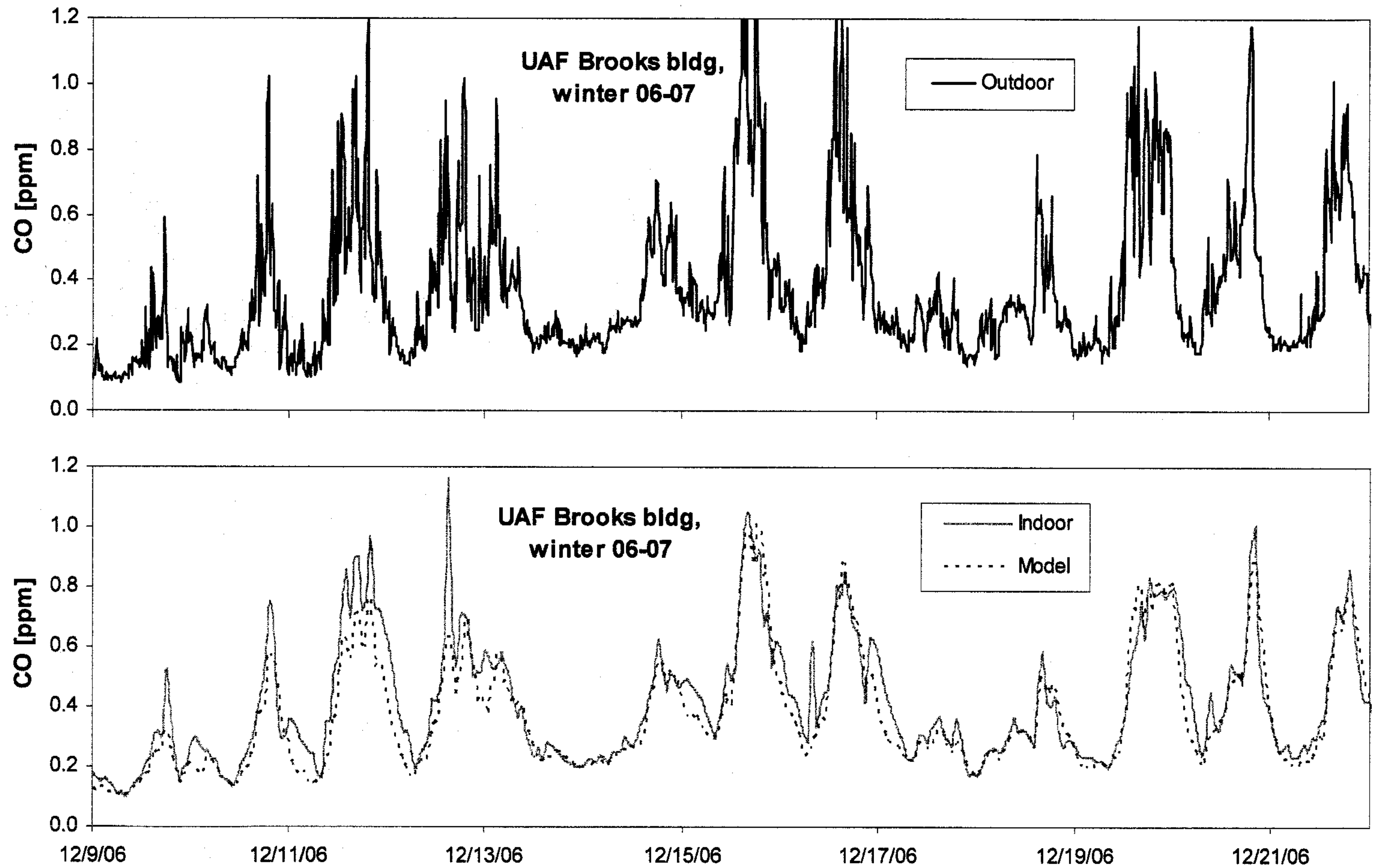

Figure A-10 Measured outdoor and indoor CO, and the state-space model output at UAF Brooks bldg in winter 06-07