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Short Communication

Penetration of Nitrogen Oxides and Particles from Outdoor into Indoor Air and Removal of the Pollutants through Filtration of Incoming Air

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Abstract We studied the effect of ventilation and air filtration systems on indoor air quality in a children's day-care center in Finland. Ambient air nitrogen oxides (NO, NO_2) and particles (TSP, PM_{10}) were simultaneously measured outdoors and indoors with automatic nitrogen oxide analyzers and dust monitoring. Without filtration nitrogen oxides and particulate matter generated by nearby motor traffic penetrated readily indoors. With chemical filtration 50–70% of nitrogen oxides could be removed. Mechanical ventilation and filtration also reduced indoor particle levels. During holidays and weekends when there was no opening of doors and windows and no particle-generating activity indoors, the indoor particle level was reduced to less than 10% of the outdoor level. At times when outdoor particle concentrations were high during weekdays, the indoor level was about 25% of the outdoor level. Thus, the possible adverse health effects of nitrogen oxides and particles indoors could be countered by efficient filtration. We also showed that inclusion of heat recovery equipment can make new ventilation installations economical.

Key words Indoor air quality; Filtration; Ventilation; Nitrogen oxides; Particles.

Practical Implications
Often child-care centers are located close to major motorways to allow easy access for parents. However, outdoor pollution from these same motorways can cause significant indoor pollution in buildings close to the motorways. This paper examines the effectiveness of air cleaning strategies to reduce indoor concentrations of nitrogen oxides and particles. The authors demonstrate reductions of particle and NOx concentrations of 65% or larger using filtration or chemical sorption.

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Introduction

Outdoor air is the source of indoor air, but relatively little is known about outdoor-indoor relationships and ways to prevent pollutant entry. In general, outdoor pollutants penetrate readily (Mukerjee et al., 1997; Lee et al., 1997; Baek et al., 1997), and they are considered important causes of bad indoor air (Burge, 1990).

In a previous study of the indoor air in a children's day-care center we found that malodorous sulfur compounds from nearby pulp mills readily diffused into the indoor air. By filtration of incoming air concentrations could be reduced to a level at which they did not cause an unpleasant sensation (Marttila et al., 1994).

Motor traffic is the worst polluter of city air. In Finland, motor traffic contributes 48% of total nitrogen oxides in outdoor air, 15% of carbon dioxide and particulate matter, and 70% of carbon monoxide (Finnish National Center for Technology Research, report in Finnish, 1996). Nitrogen oxides and particulates are widely distributed, they are not local problems like the malodorous sulfur compounds. Indoor particle sources are major contributors to particle concentrations.

In the present study we examined the penetration of outdoor nitrogen oxides and particles into the indoor air. We tested methods to prevent their entry by adding various filters to a controlled ventilation system and examined the economics of improved ventilation systems.

Material and Methods

Site

The study was carried out in 1998 at the Mansikkala children's day-care center in the city of Imatra. The

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center is close to a busy intersection. Pollutants had not previously been measured in Mansikkala, but measurements at similar locations elsewhere in Imatra suggested the presence of moderate concentrations of nitrogen oxides and concentrations of particles that occasionally exceeded Finnish guideline values. In 1997, the yearly mean concentrations in Imatra were 20 μg/m^3 for both nitrogen monoxide (NO) and nitrogen dioxide (NO_2), 38 μg/m^3 for total suspended particulates (TSP), and 24 μg/m^3 for particles with a diameter under 10 μm (PM_{10}). Highest 24-h means were 118 μg/m^3 NO, 59 μg/m^3 NO_2, and 142 μg/m^3 TSP (City of Imatra, report in Finnish, 1998). The 98th percentile for TSP 24-h means was 157 μg/m^3, and the second highest PM_{10} 24-h mean in a one-month period for PM_{10} was 88 μg/m^3; these two values exceed the guideline values 120 μg/m^3 TSP and 70 μg/m^3 PM_{10} (Regulations of State No. 476–482, 1996).

The section of the children's day-care center that was studied had an area of 70 m^2. The section included two bedrooms (resting rooms), an activities room, a dressing room, and a bath/toilet area. The section had its own entrance and porch, and there was a door to other sections of the center. During the study the section operated as usual, and 14 children and 4 or 5 adults were present on weekdays. Efforts were made to avoid unnecessary opening of windows and doors. The center has vinyl floor covering. Floors, tables, and other horizontal surfaces were wiped daily with a moist mop or sponge. Once a week carpets and bedding were given an airing, and floors were washed.

Ventilation and Filters

For the purposes of the study we installed a controlled mechanical incoming and exhaust air system, which included equipment for heat recovery (MUH Lämpöilmava, Vallox Oy, Finland). Depending on ventilation volumes, 10–30% indoor air could be recirculated. Volumes were adjusted to the 5 l/s/person required in children's day-care centers (Ministry of the Environment, 1987).

Mechanical intake and exhaust, mechanical filters

To study the effects of mechanical filtration two filter units were used: a coarse filter (EU1, Vallox Oy, Finland) in the incoming duct and a fine (EU5) filter in the machinery. The EU1 filter removed 10–120 μm particles, and the EU5 filter removed maximally 40% of particles below 2 μm. Recirculation of indoor air was eliminated.

Mechanical intake and exhaust, mechanical and chemical filters

To study the effects of chemical filtration a gas filtration unit was added. The Purafil CP® (Vallox Oy, Finland) filter material consisted of carbon (C) and aluminum oxide (Al_2O_3) saturated with potassium permanganate ($KMnO_4$). The filter oxidizes gaseous compounds. Simultaneously the mechanical EU1 and EU5 filters, and a third mechanical filter, EU7, were in use. The EU7 removes 65% of particles below 0.5 μm and nearly 100% of particles below 2 μm. Twenty percent (15 l/s) indoor air was recirculated.

Mechanical exhaust, mechanical filter

A simple ventilation system was examined by running only the exhaust fan while other fans were off. The coarse EU1 filter remained active in the incoming duct.

Nitrogen Oxide and Particle Measurements

To study the penetration of pollutants we measured NO, NO_2, TSP, and PM_{10} simultaneously in outdoor and indoor air. Continuously recording analyzers and monitors were used. Nitrogen oxides (NO_x) were detected using chemiluminescence (Horiba Apna 360 analyzer, Horiba Ltd., Japan) and particles using beta radiation absorption (Eberline FH 62 I-R monitor, Eberline Instruments GmbH, Germany). Data were collected in the form of 2-min means. The coefficient of variation was estimated to be 10% for nitrogen oxide measurements and 20% for particulates. The nitrogen oxide analyzer was calibrated six times and the particle monitor twice during the study.

Two NO_x analyzers, one for indoor and one for outdoor measurements, and a particle monitor for outdoor measurements were placed in a box outside the center. One particle monitor was indoors. For NO_x measurements there was an outdoor air intake close to the building ventilation intake 2 m above ground. For indoor NO_x measurements there was an intake 1.5 m above the floor in the middle of the locality. From the intakes air was carried to the NO_x analyzers via teflon tubing. For outdoor particle measurements the air was sampled 3 m above ground, 1.5 m from the building intake. For indoor particle measurements the air was sampled 1.5 m above the floor. Air was conducted to the particle monitors via straight steel tubes.

Measurement Periods and Data Analysis

Pollutant quantities outdoors and indoors were measured using three ventilation/filtration systems: (1) mechanical exhaust ventilation with a coarse filter in the incoming duct; (2) mechanical intake and exhaust ventilation with two mechanical filters; and (3) mechanical intake and exhaust ventilation with one chemical and three mechanical filters and 20% recirculation. NO and NO_2 were both measured during two periods

Table 1 Nitrogen monoxide (NO) concentrations measured simultaneously outdddors and indoors during weekdays, during weekends and holidays, and during periods with a high outdoor NO level (above 50 µg/m³). Measurements were made with three ventilation/filtration systems during separate periods

Ventilation/ filtration system	Number of 1-h registered means	NO concentration (µg/m³)				Outdoor–indoor difference		Compared with mechanichal exhaust (P)	Compared with mechanical filtration (P)	Filtration efficiency (%)
		Outdoor		Indoor						
		Mean	SD	Mean	SD	Mean	SD			
Mechanical exhaust, mechanical filter										
Weekends & holidays	216	9.8	22.6	8.4	20.3	1.4	7.8			14
Weekdays	184	21.2	40.7	13.4	31.5	7.8	20.8			37
High outdoor NO	61	138.0	91.4	113.6	79.2	24.4	53.3			18
Mechanical intake and exhaust, mechanical filter										
Weekends & holidays	336	5.4	10.8	4.1	10.1	1.3	4.8	*		24
Weekdays	348	13.2	23.0	6.1	15.8	7.1	9.9	*		59
High outdoor NO	28	129.0	96.8	102.3	88.2	26.6	36.9	0.841		21
Mechanical intake and exhaust, mechanical and chemical filter										
Weekends & holidays	432	6.2	11.7	2.9	5.3	3.2	7.3	*	<0.001	52
Weekdays	391	18.5	32.2	5.8	12.7	12.7	21.9	<0.05	*	69
High outdoor NO	85	113.0	66.5	40.5	28.4	72.7	48.4	<0.001	<0.001	64

* Outdoor concentrations observed during periods with different filtration differed too much to allow valid comparisons

Table 2 Nitrogen dioxide (NO_2) concentrations measured simultaneously outdoors and indoors during weekdays, during weekends and holidays, and during periods with a high outdoor NO_2level (above 50 µg/m³). Measurements were made with three ventilation/filtration systems during separate periods

Ventilation/ filtration system	Number of 1-h registered means	NO concentration (µg/m³)				Outdoor–indoor difference		Compared with mechanichal exhaust (P)	Compared with mechanical filtration (P)	Filtration efficiency (%)
		Outdoor		Indoor						
		Mean	SD	Mean	SD	Mean	SD			
Mechanical exhaust, mechanical filter										
Weekends & holidays	216	18.2	24.6	11.4	11.1	6.8	14.4			38
Weekdays	184	23.5	18.3	18.4	9.2	5.1	11.4			22
High outdoor NO_2	101	72.5	12.9	36.1	7.4	36.4	8.7			50
Mechanical intake and exhaust, mechanical filter										
Weekends & holidays	336	16.8	15.3	15.9	12.1	1.0	6.1	<0.001		6
Weekdays	348	21.9	14.0	23.8	12.1	−1.9	9.9	<0.001		−9
High outdoor NO_2	69	62.8	9.5	48.9	16.2	13.9	17.7	*		22
Mechanical intake and exhaust, mechanical and chemical filter										
Weekends & holidays	432	18.1	22.8	8.8	7.2	9.4	16.9	0.053	<0.001	52
Weekdays	391	23.7	16.5	12.5	6.8	11.3	12.5	<0.001	<0.001	48
High outdoor NO_2	162	74.2	17.9	25.6	6.8	48.6	6.4	<0.001	*	66

* Outdoor concentrations observed during periods with different filtration differed too much to allow valid comparisons

with each of the three ventilation systems, and averages for the two periods are reported in the tables. TSP and PM_{10} were measured during one period.

Data were treated separately for periods when: (1) the day-care center was not in operation (weekends and holidays); (2) the day-care center was in operation (weekdays 7 a.m. to 5 p.m.); and (3) outdoor air contained high concentrations of nitrogen oxides (above 50 µg/m³) or particulates (above 20 µg/m³).

Definitions: Filtration efficiency %=(outdoor concentration−indoor concentration)/outdoor concentration×100%. The coefficient of variation=standard deviation/mean×100%. The standard deviation is abbreviated SD.

Results

Penetration of Nitrogen Oxides

Outdoor nitrogen oxide concentrations observed during the study were relatively low. The NO mean was 13.6

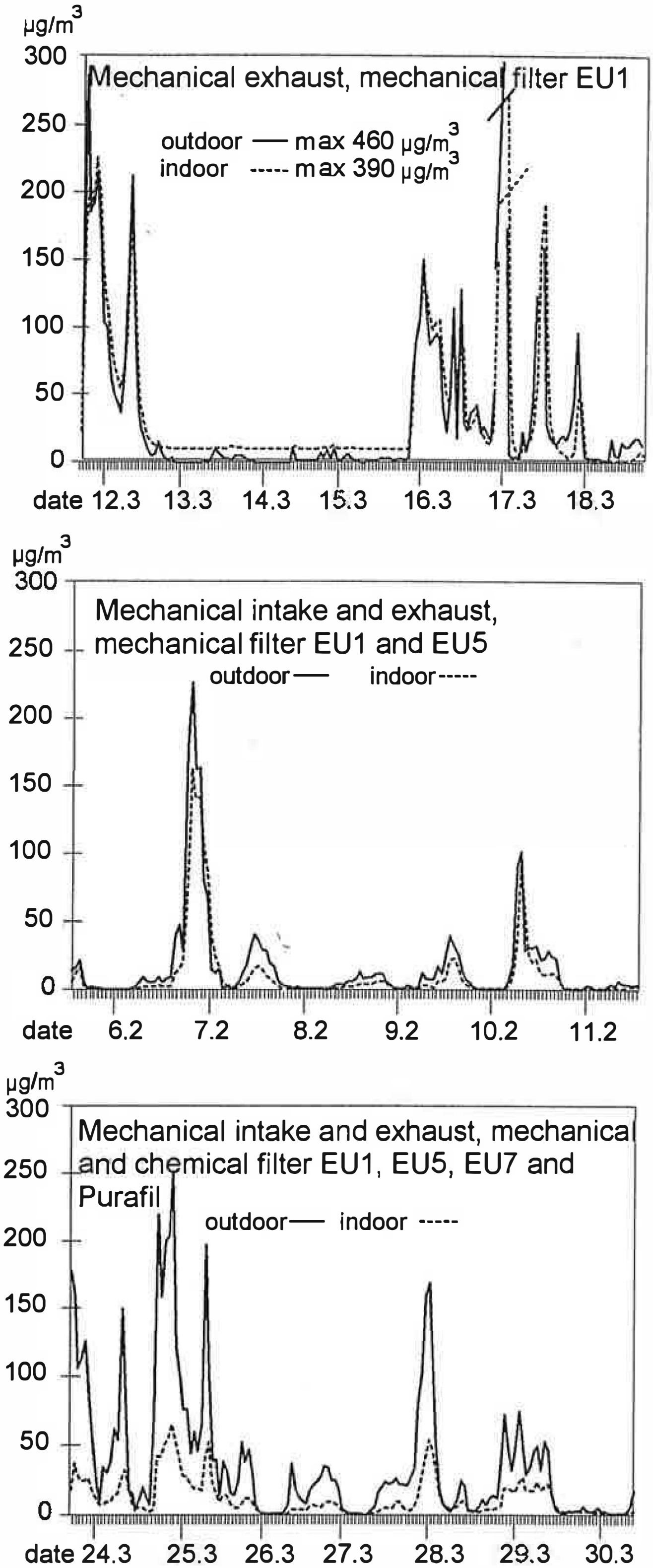

Fig. 1 Nitrogen monoxide (NO) concentrations measured simultaneously outdoors and indoors during 6- to 7-day periods. Measurements were made with three ventilation/filtration systems during separate periods. Values are 1-h means

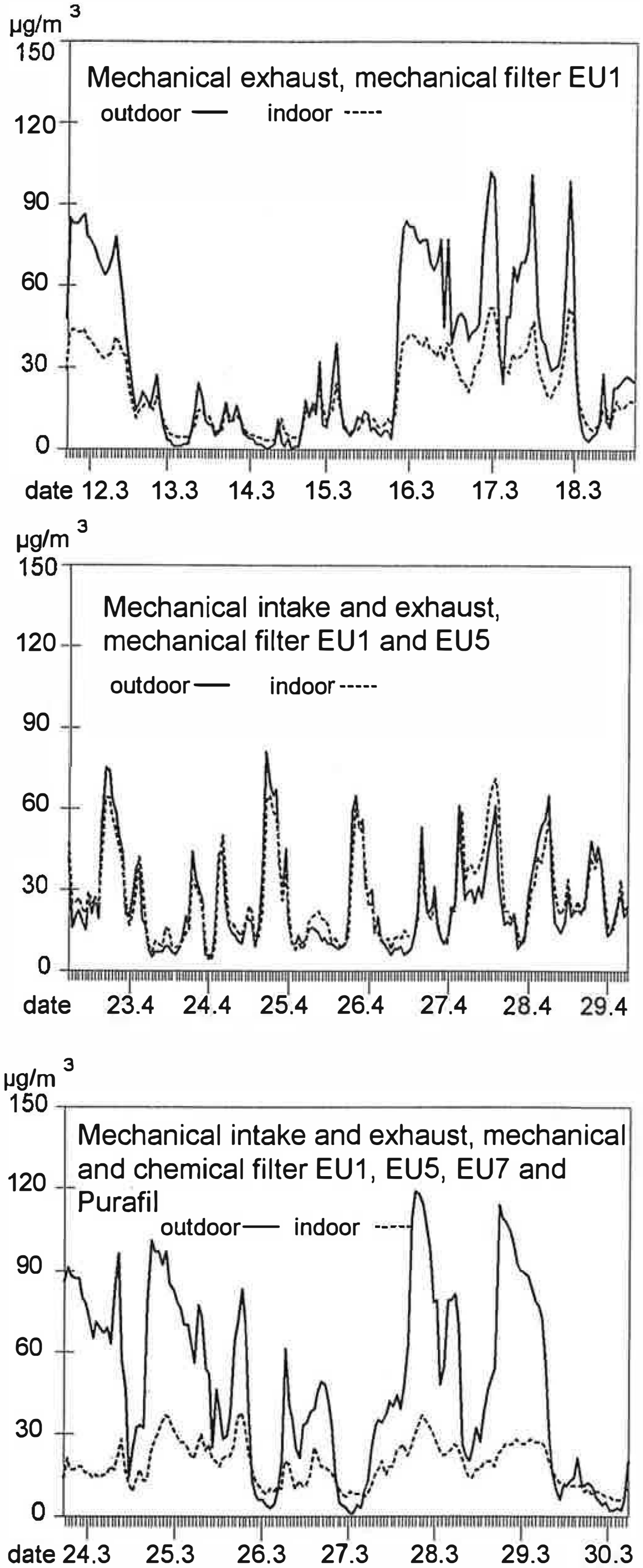

Fig. 2 Nitrogen dioxide (NO_2) concentrations measured simultaneously outdoors and indoors during 6- to 7-day periods. Measurements were made with three ventilation/filtration systems during separate periods. Values are 1-h means

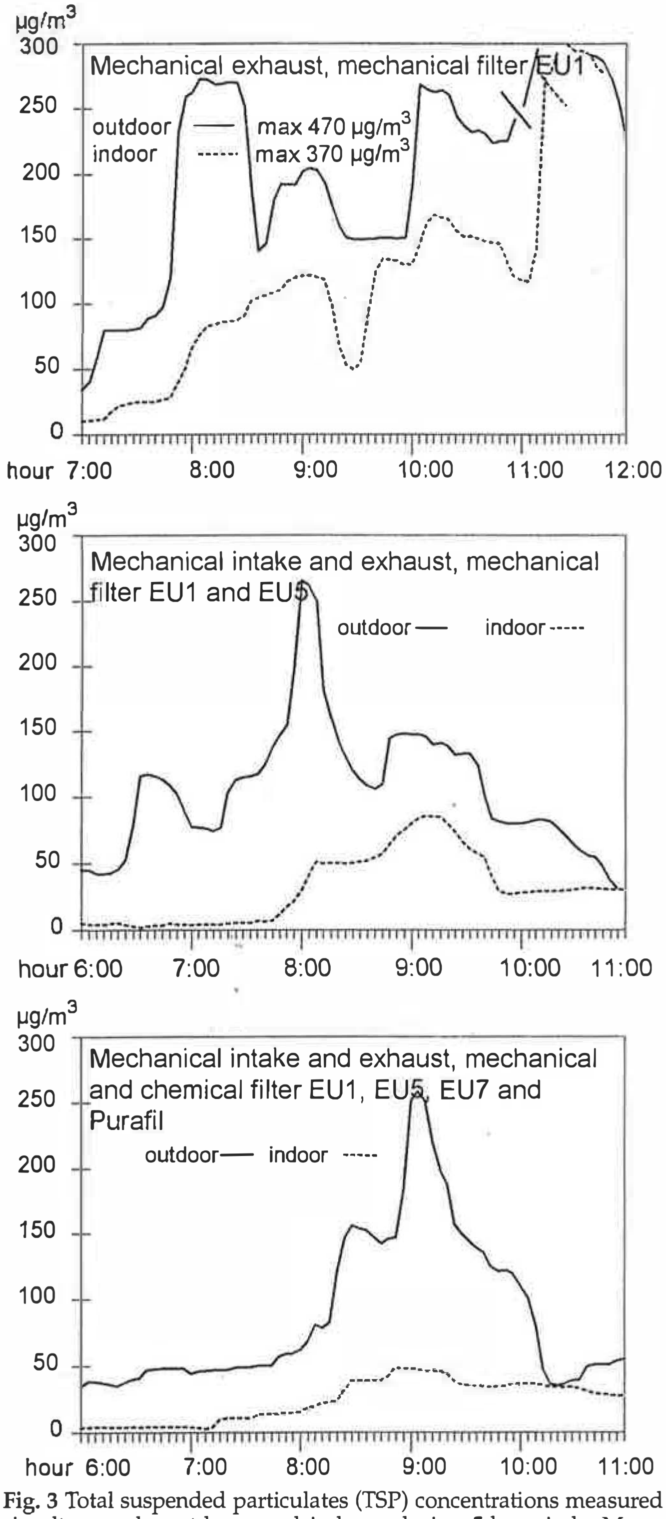

Fig. 3 Total suspended particulates (TSP) concentrations measured simultaneously outdoors and indoors during 5-h periods. Measurements were made with three ventilation/filtration systems during separate periods. Values are 4-min means

µg/m^3 (SD 34.8 µg/m^3) and the NO_2 mean 21.0 µg/m^3 (SD 21.3 µg/m^3).

Nitrogen oxides readily penetrated into the building when only mechanical filtration was used. The two ventilation systems with only mechanical filtration removed 18 and 21% NO respectively when the outdoor NO level was high (Tables 1 and 2). With chemical Purafil CP® filtration indoor concentrations were reduced substantially. When outdoor nitrogen oxide concentrations were high, filtration removed 64% NO and 66% NO_2 (Figures 1 and 2, Tables 1 and 2).

All ventilation systems removed a higher percentage of NO from the incoming air during weekdays than during weekends and holidays. This was probably due to higher outdoor concentrations on weekdays. NO_2 filtration was about equally efficient on weekdays and during weekends (Tables 1 and 2).

Particulates

During the study the outdoor TSP mean was 46.8 µg/m^3 (SD 48.6 µg/m^3) and the PM_{10} mean was 26.2 µg/m^3 (SD 23.9 µg/m^3). Variations in outdoor particle concentrations complicated filtration efficiency comparisons between experimental periods.

During holidays and weekends indoor particle levels were very low, and the filtration efficiencies of all ventilation systems were good, above 70%. TSP filtration efficiency was best with mechanical filtration only (94%), while PM_{10} filtration efficiency was best (89%) with added chemical filtration and 20% recirculation of indoor air (Tables 3 and 4).

On weekdays opening of doors and windows and indoor particle-generating activities and resuspension increased indoor particle concentrations. When day-care center activities started in the morning between 7 and 8, indoor particle concentrations began to rise. In addition to the activities, also rising outdoor concentrations contributed. Even so, indoor particle concentrations remained well below outdoor concentrations when mechanical intake and exhaust combined with filtration was applied. Best results were seen with when chemical filtration and recirculation were included and then at high outdoor concentrations, the indoor TSP level was 73% below the outdoor level and the PM_{10} level was 79% lower. Mechanical exhaust alone combined with a filter in the incoming duct was rather inefficient, indoor particle concentrations could momentarily be even higher than outdoor concentrations (Figure 3, Tables 3 and 4).

Economy

The MUH Lämpöilmava equipment and its installation cost USD 5,000. Before its installation, with no heat recovery, energy expenditure was 16,500–17,500 kWh/a. The new equipment reduced the use of energy by about 60%. Mechanical filters in the new equipment need replacement twice a year. The fine filters EU5 and EU7 cost USD 40 each, and the coarse filter EU1 costs USD

7. The chemical Purafil filter can be used for one to two years and costs USD 200.

Adding a 5% yearly write-off (USD 250) to the yearly cost for filters (USD 350) totals USD 600. The new equipment brought an energy saving of 10,000 kWh/a worth about USD 500. Thus, under the conditions of our study, 83% of the cost for a new and better ventilation system was paid for by reduced energy expenditure.

Discussion

Outdoor nitrogen oxides, largely from motor traffic, readily penetrated into the children's day-care center that we studied. With a ventilation system that included chemical filtration of incoming air the indoor nitrogen oxide levels could be reduced to about 35% of outdoor levels at times when outdoor levels were high. Unfiltered air entered, unavoidably, as doors were opened.

Much the same was true for particles. The two fully mechanical ventilation systems that were tried kept indoor particle levels at about 30% of the outdoor level, when outdoor levels were high. This was true also for particles with a diameter under 10 μm (PM_{10}), which penetrate into the lower airways. Indoor particle sources, activities causing resuspension of particles, and opening of doors increased indoor levels. During week-

Table 3 Total suspended particulates (TSP) concentrations measured simultaneously outdoors and indoors during weekdays, during weekends and holidays, and during periods with an outdoor TSP concentration above 20 μ/m₃. Measurements were made with three ventilation/filtration systems during separate periods

Ventilation/ filtration system	Number of 1-h registered means	TSP concentration (μg/m³)				Outdoor–indoor difference		Filtration efficiency (%)
		Outdoor		Indoor				
		Mean	SD	Mean	SD	Mean	SD	
Mechanical exhaust, mechanical filter								
Weekends & holidays	24	21.0	13.5	2.8	1.8	18.2	12.2	87
Weekdays	30	166.3	150.8	80.4	54.3	85.9	142.9	52
High outdoor TSP	72	103.2	118.0	38.0	50.3	65.7	100.7	64
Mechanical intake and exhaust, mechanical filter								
Weekends & holidays	87	43.1	25.0	2.6	2.0	40.5	24.5	94
Weekdays	86	66.5	39.9	40.6	30.1	25.9	46.0	39
High outdoor TSP	216	55.7	31.7	17.6	25.9	38.1	33.5	68
Mechanical intake and exhaust, mechanical and chemical filter								
Weekends & holidays	96	42.6	18.4	5.7	2.4	36.9	16.9	87
Weekdays	86	36.5	25.8	20.5	14.7	16.0	31.5	44
High outdoor TSP	215	42.8	22.5	10.3	10.4	32.6	24.9	73

Table 4 Concentration of particles with a diameter under 10 μm (PM_{10}) measured simultaneously outdoors and indoors during weekdays, during weekends and holidays, and during periods with an outdoor PM_{10} concentration above 20 μg/m³. Measurements were made with three ventilation/filtration systems during separate periods

Ventilation/ filtration system	Number of 1-h registered means	PM_{10} concentration (μg/m³)				Outdoor–indoor difference		Filtration efficiency (%)
		Outdoor		Indoor				
		Mean	SD	Mean	SD	Mean	SD	
Mechanical exhaust, mechanical filter								
Weekends & holidays	87	9.6	12.2	2.7	2.1	6.9	11.0	72
Weekdays	62	15.4	13.5	32.6	23.2	−17.2	25.9	−13
High outdoor PM_{10}	42	33.0	14.1	16.4	23.9	16.6	27.6	50
Mechanical intake and exhaust, mechanical filter								
Weekends & holidays	119	39.4	23.8	6.8	2.8	32.6	22.4	83
Weekdays	111	46.7	24.7	31.6	17.0	15.2	29.1	33
High outdoor PM_{10}	303	48.5	32.5	15.2	15.0	33.3	34.0	68
Mechanical intake and exhaust, mechanical and chemical filter								
Weekends & holidays	139	20.6	24.6	2.3	1.9	18.4	23.9	89
Weekdays	87	28.1	43.6	16.6	13.2	11.5	45.5	41
High outdoor PM_{10}	131	44.6	42.4	9.3	11.4	35.3	44.3	79

ends, when the day-care center was not in use, particle levels were very low.

The best overall result was achieved with a combination of mechanical filters and a chemical Purafil CP® filter. In a previous similar study, we examined the penetration and removal of malodorous sulfur compounds and found that all but a few percent of the compounds could be removed from incoming air with the Purafil filter. Methods should be further developed to enable the removal of other common pollutants such as sulfur dioxide, carbon monoxide, ozone, and volatile organic compounds.

We observed that inclusion of heat recovery into a new and efficient ventilation system – under the conditions our study – resulted in savings that covered 83% of the costs for installing and operating the new equipment.

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