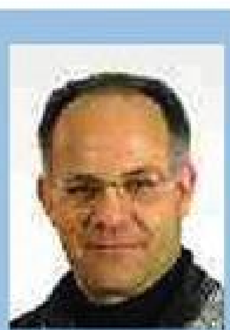
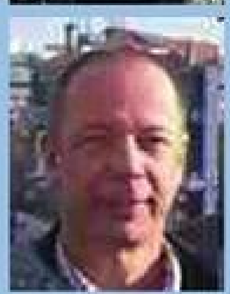
Naborøg og overførsel af partikelforurening

Det er vigtigt at reducere overførslen af luft mellem etageboliger, så risikoen for at blive udsat for passiv rygning nedbringes, og boligernes luftkvalitet forbedres. I denne undersøgelse kvantificeres overførelsesluften og risikoen for overførsel af partikelforurening. Endvidere udarbejdes der vejledninger om de bedste ventilationstekniske og byggetekniske tiltag til reduktion af overførsel af luft mellem lejligheder

Af Alireza Afshari og Niels C. Bergsøe, SBi, Aalborg Universitet, afdelingen for Energi og miljø og Bingbing Shi og Lars Ekberg, Chalmers Tekniska Högskola, Installationsteknik, Göteborg

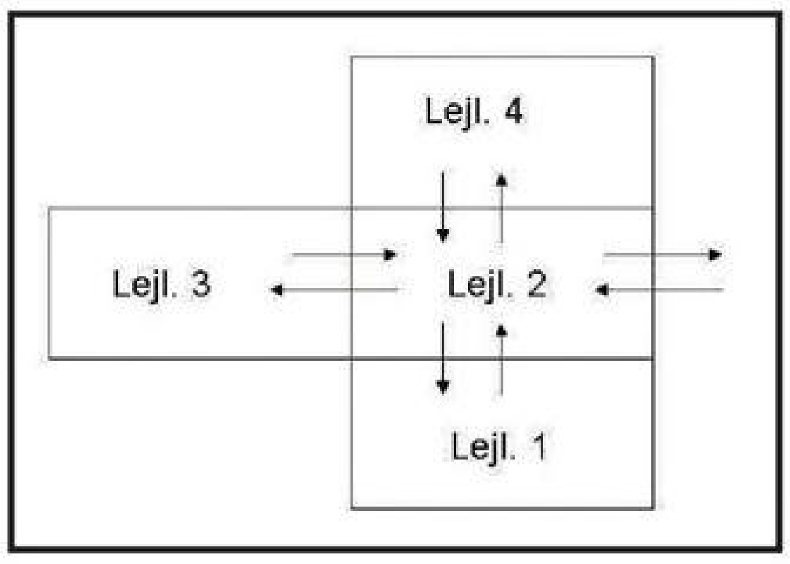
Det er ikke ualmindeligt at beboere i etageejendomme oplever generende lugte knyttet til naboens aktiviteter, fx madlavning. Problemet er særlig alvorligt, når det også drejer sig om sundhedsskadelige stoffer, såsom partikler fra tobaksrygning.

Det kaldes passiv rygning, når man ufrivilligt udsættes for luft forurenet med andres tobaksrøg. Studier har vist, at rygning kan give høje koncentrationer af ultrafine partikler (UFP). Miljømedicinske undersøgelser tyder på, at eksponering for tobaksrøg er en betydelig kilde til sygelighed og dødelighed i EU og i Danmark. Det medfører store udgifter for samfundet som helhed.

I et tidligere forskningsprojekt udførte SBi målinger i en ældre bygning, hvor mere end halvdelen af den tilførte luft var "brugt" luft fra andre lejligheder og trappeopgange. Luften kom ind i lejligheden gennem utætheder. "Brugt" luft har ikke udeluftens evne til at fjerne forureninger og fugt, og det giver risiko for dårlig luftkvalitet. Også i nye etageboliger kan tilsvarende problemer forekomme.

Derfor er det vigtigt at fokusere på at reducere overførslen af luft mellem etageboliger, dels for at nedbringe risikoen for udsættelse for passiv rygning, dels af hensyn til luftkvaliteten i boligerne.

Formålet med denne undersøgelse er at kvantificere overførelsesluften og risikoen for overførsel af partikelforurening, og at udarbejde vejledninger om de bedste ventilationstekniske og byggetekniske tiltag til reduktion af overførsel af luft mellem lejligheder.



Figur 1. Skitse af en komplet unit. lejl.= Lejlighed

Metoder

Der blev udvalgt 19 etageboliger i 7 trappeopgange i 6 bygninger (A til F) bygget mellem 1860 og 1934. De udvalgte lejligheder var i ikke-renoverede og renoverede bygninger. Her præsenteres målingerne i bygning A, B, D og E. Resultaterne fra bygning C og F behandles ikke i denne artikel.

Kilder til generering af partikler bestod af cigaretter og stearinlys. Målingerne med cigaretter blev foretaget i ubeboede lejligheder i en ikke-renoveret bygning (bygning A). Målingerne med stearinlys blev både foretaget i renoverede og ikke-renoverede lejligheder (bygning B, D og E). Der blev også målt luftskifte, CO_2, temperatur- og luftfugtighed over en uge. Målingerne blev foretaget i februar og marts 2008.

Koncentrationer af ultrafine partikler blev målt vha. tre partikeltællere. Én var placeret i kildelejligheden (lejligheden hvor partiklerne blev genereret), én i eksponeringslejligheden (lejligheden som blev infiltreret af partikler fra kildelejligheden) og én blev brugt til ▷

$$c_{r(t)} = \frac{c_s \dot{V}}{\dot{V} + rV} + \frac{\dot{M}}{\dot{V} + rV} - \frac{\dot{V}}{\dot{V} + rV}\left[c_s + \frac{\dot{M}}{\dot{V}} - \frac{\dot{V} + rV}{\dot{V}} c_{r(0)}\right] e^{-\left[\frac{\dot{V}}{V} + r\right]t} \qquad (1)$$

hvor:

$\dot{V}$ = luftstrøm, m^3/h

$\dot{M}$ = Overføring af partikler mellem lejligheder, $[(p/m^3) * (m^3/h)]$

c_s = koncentration af UFP i tilluften, p/m^3

c_r = koncentration af UFP i lejligheden, p/m^3

V = lejlighedens volumen, m^3

r = fjernelse af partikler, h^{-1}

Ligning 1.

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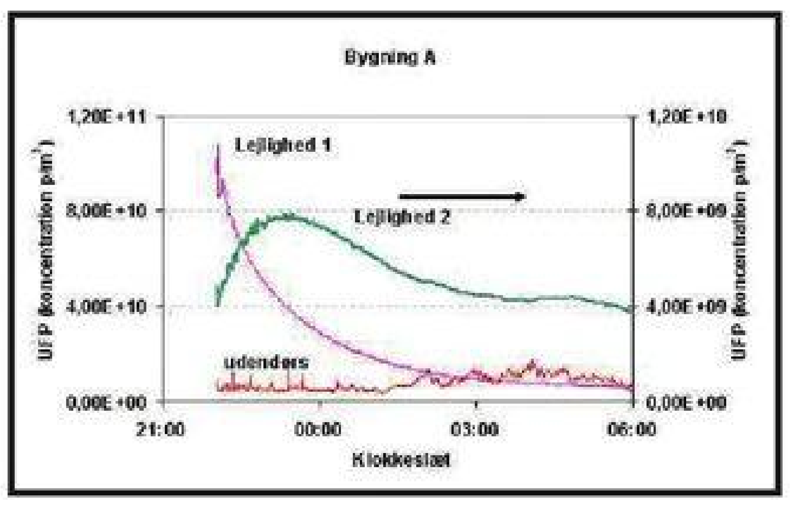


Figur 2. Målt koncentration af UFP i lejlighed 1 og 2 samt udendørs ved bygning A.

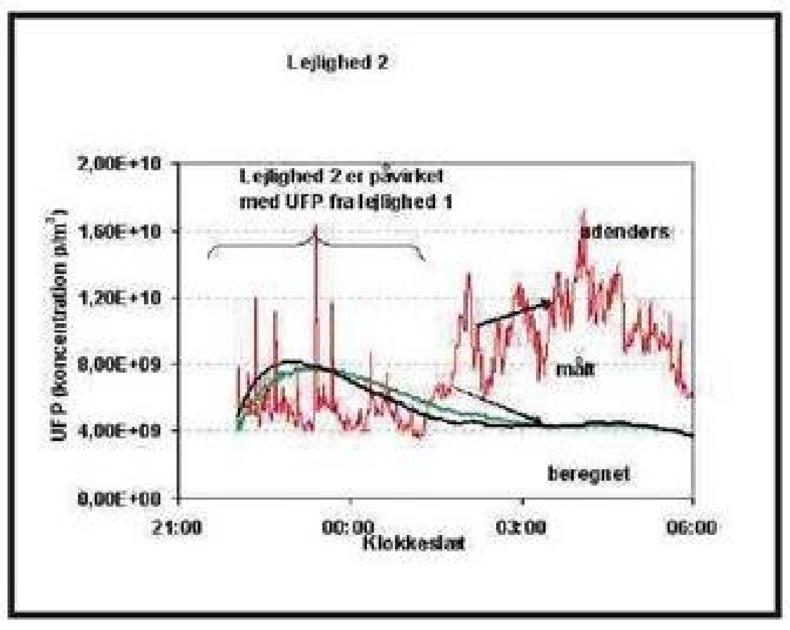
måling af partikler udendørs. To af partikeltællerne var TSI model P-trak 8025, og den tredje var CPC 3007.
Figur 1 illustrerer en komplet unit af lejligheder. I bygning A anvendes en komplet unit. I de andre bygninger anvendes kun lejlighed 1 og lejlighed 2 i undersøgelsen.

Resultater

Måling og beregning af UFP-koncentrationen
Figur 2 viser de opmålte koncentrationsforløb for cigaretrøg i lejlighed 1 (kildelejligheden) og lejlighed 2 (eksponeringslejligheden). To cigaretter var tændt i lejlighed 1, den ene i stuen og den anden i soveværelset. Baggrundskoncentration i lejlighed 2 var ca. 4,0E+09 p/m^3 (partikler pr. m^3) om natten.
For at kunne beregne eksponeringskoncentrationen er det nødvendigt at beskrive måleresultaterne matematisk vha. en model. Figur 3 illustrerer målt og beregnet UFP-koncentration i eksponeringslejligheden. Beregningerne er udført ifølge ligning 1, side 24. Det er forudsat, at der er fuldstændig opblanding af partikler og luft. Denne forudsætning indebærer, at udsugningsluftens UFP-koncentration er lig med lejlighedsluftens koncentration.
Modellen bruges til beregning af UFP-koncentrationen i de undersøgte lejligheder.
Tabel 1 til 3 viser målte og beregnede parametre af cigaretrøg i eksponeringslejlighederne i bygning A, B, D og E.
Anden kolonne i tabel 1 og 3 viser eksponeringen. Det er den procentvise andel af de ultrafine partikler, der genereres i kildelejligheden, og som infiltrerer eksponeringslejligheden.

	Eksponering (Infiltration) i lejl.2 (%)	Fjernelse af UFP i lejl. 2 (1/h)	Luftskifte i lejl. 2 (1/h)	Lækage (m^3/h)
Fra lejl.1 til lejl.2	8,6	0,9	0,41	14
Fra lejl.4 til lejl.2	1,8	1,5	0,41	5
Fra lejl.3 til lejl.2	1,1	1,4	0,41	5

Tabel 1. Målte og beregnede parametre af cigaretrøg i eksponeringslejligheden i bygning A.



Figur 3. Resultat af måling og beregning af UFP-koncentrationen i lejlighed 1 og 2 i bygning A.

	Eksponering (Infiltration inkl. reduktion ved drift af AC) (%)	Fjernelse af UFP i lejl. 2 (1/h)	Luftskifte i lejl. 2 (1/h)	Lækage (m^3/h)
Fra lejl.1 til lejl.2 1 AC i lejl.1	5,0	1,0	0,41	15
Fra lejl.1 til lejl.2 1 AC i lejl.2	4,2	1,9	0,41	15
Fra lejl.1 til lejl.2 2 AC i lejl.2	2,6	3,9	0,41	16

Tabel 2. Målte og beregnede parametre af cigaretrøg i eksponeringslejligheden i bygning A. Med luftrensere.

	Eksponering (Infiltration) i lejl.2 (%)	Fjernelse af UFP i lejl. 2 (1/h)	Luftskifte i lejl. 2 (1/h)	Lækage (m^3/h)
Fra lgh.1 til lejl.2 Bygning B	2,6	2,7	0,74	10
Fra lgh.1 til lejl.2 Bygning D	0,3	4,4	0,92	2,3
Fra lgh.1 til lejl.2 Bygning E	0,7	1,5	0,36	5

Tabel 3. Målte og beregnede parametre af stearinlys i eksponeringslejlighed i bygning B, D og E. Bygning B var ikke renoveret, bygning D almindelig renoveret og bygning E total-renoveret.

Eksponeringen vises i anden kolonne i tabel 2, og omfatter infiltration inklusive reduktion pga. AC-drift. Størrelserne beregnes ved at sammenligne det totale antal tobaksrelaterede partikler i eksponeringslejligheden med det totale antal tobaksrelaterede partikler i kildelejligheden.
Tredje kolonne viser summen af deponering, ventilationens borttransport og andre mekanismer, som reducerer luftens indhold af UFP.
Fjerde kolonne viser luftskiftet i eksponeringslejlighederne.
Sidste kolonne viser luftoverførslen forårsaget af en lækage fra kildelejlighederne til eksponeringslejlighederne. Luftskiftet og luftoverføringen er ugemiddelværdier.
Rækkerne 2 til 4 i tabel 1 viser kildelejlighederne i successive undersøgelser. Kilderne var placeret i lejlighed 1, 4 og 3.
Tabel 2 viser målte og beregnede parametre af cigaretrøg i eksponeringslejligheden i bygning A. Undersøgelsen er gennemført i lejlighed 1 og lejlighed 2 i bygning A.
Kolonne 1 i tabel 2 viser antal luftrensere (AC; Air Cleaner) anbragt i kildelejligheden eller i eksponeringslejligheden.

Betydningen af luftrensere
Et andet formål var at kortlægge ventilationsforhold og lufttæthed, og derved beskrive nye tekniske løsninger til afprøvning i ikke-renoverede lejligheder/bygninger. Boligselskabet ønskede ikke at medvirke ved af- ▷

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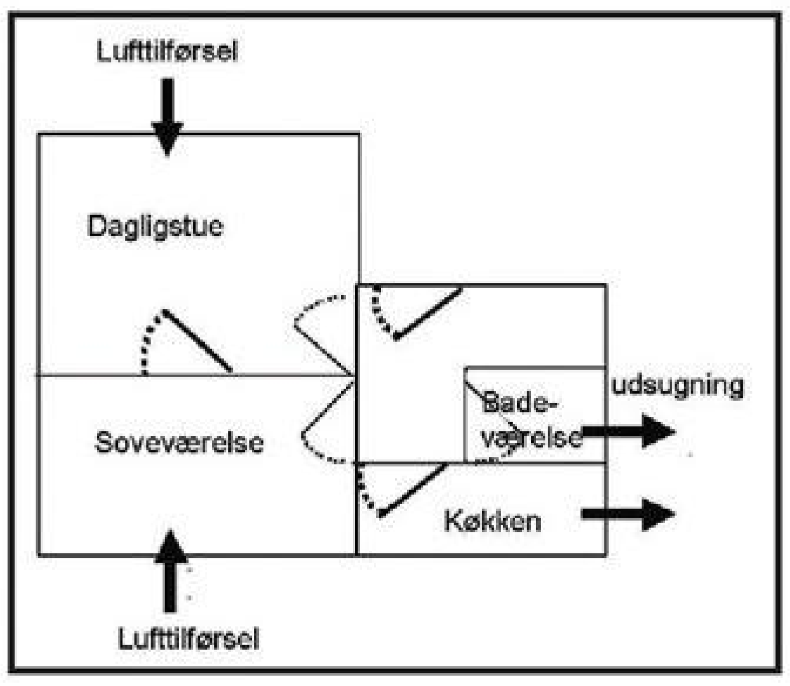
prøvningen, derfor blev der to renoverede bygninger, D og E, udvalgt og undersøgt. Målet var at undersøge, hvordan renovering af bygninger kan påvirke UFP-infiltrationen mellem to lejligheder.
Luftrensere bruges til at reducere koncentrationen af UFP i rumluften. Det er undersøgt, hvordan placeringen af luftrensere i forskellige rum kan ind-



Figur 4. Skitse af den studerede lejlighed i bygning A.

virke på reduktionen af koncentrationen af UFP i kildelejligheden. Tabel 4 og 5 viser resultaterne. Der bruges to elektriske luftrensere (ifølge fabrikanten har hver luftrenser en Clean Air Delivery Rate på CADR=240 m^3/h).
Undersøgelsen består af forskellige situationer, hvor cigaretrøg og luftrenser enten var i samme rum eller i forskellige rum, åbne eller lukkede rum og med brug af en eller to luftrensere.
Værdierne i tabel 4 og 5 er baserede på en beregning af partik-

Dørposition	Driftsituation AC	Eksponering i forhold til eksponering i køkken uden luftrenser	
		Eksponering i køkken	Eksponering i soveværelse
Dør til køkken åben	Ingen AC	100%	102%
	1 AC i køkken	88%	78%
Dør til køkken lukket	Ingen AC	163%	5%
	1 AC i køkken	40%	4%

Tabel 4. Eksponering af UFP i køkken og soveværelse. Resultaterne er udtrykt i % af eksponeringen i køkkenet uden luftrenser og med åben dør. Cigaretrøgen blev genereret i køkkenet.

eleksponeringen, mens der var tobaksrøg i lejligheden. Partikelkoncentrationen var forhøjet i ca. tre timer, efter cigaretten blev røget. Eksponeringen bestemmes derfor som den totale mængde partikler, der findes i luften, fra det tidspunkt cigaretten bliver tændt og tre timer frem.
Af tabel 4 fremgår det, at eksponeringen for partikler var nogenlunde ens i køkken og soveværelse, når dørene mellem disse rum var åbne, selvom cigaretten blev røget i køkkenet. Når døren var lukket, faldt partikelkoncentrationen i soveværelset markant. Resultaterne fra forsøget med lukket dør viser også, at koncentrationen i køkkenet var ca. 75 % lavere, når der blev brugt luftrenser, sammenlignet med situationen uden luftrenser og lukket dør.
Tabel 5 sammenfatter resultaterne fra en serie forsøg med generering af cigaretrøg i dagligstuen. I alle måleserierne var døren mellem dagligstue og soveværelse lukket. Dørene ud til entreen var åbne (figur 4). Når én luftrenser var i drift faldt partikeleksponeringen i dagligstuen til 37 % af eksponeringen uden luftrenser, og ved to luftrensere i drift faldt eksponeringen til 29 %. Det er ikke klarlagt, hvorfor effekten af den an-

Dørposition	Driftsituation AC	Eksponering i forhold til eksponering i dagligstue uden luftrenser	
		Eksponering i dagligstue	Eksponering i soveværelse
Dør mellem dagligstue og soveværelse lukket	Ingen AC	100 %	85 %
	1 AC i dagligstue	37 %	31 %
	2 AC i dagligstue	29 %	25 %
	2 AC i soveværelse	45 %	10 %

Tabel 5. Eksponering af UFP i dagligstue og soveværelse. Resultaterne er udtrykt i % af eksponering i dagligstuen uden luftrenser. Cigaretrøgen blev genereret i dagligstuen.

den luftrenser var mindre end den beregningsmæssigt forventede effekt, nemlig 23 %.
Tabel 5 viser, at eksponeringen i soveværelset i de fleste tilfælde var noget mindre end i dagligstuen. At der ikke var større forskel mellem soveværelse og dagligstue skyldes formodentlig, at begge rums døre var åbne ud til entreen. Der var altså ingen direkte kontakt mellem dagligstue og soveværelse, så tobaksrøg fra dagligstuen spredtes til soveværelset via entreen. Dette resultat kan sammenlignes med resultatet i tabel 4, der viser, at spredningen af tobaksrøg fra køkkenet til soveværelset var meget begrænset, når køkkendøren var lukket. I dette tilfælde fandtes der ikke andre åbninger for spredning af tobaksrøg fra køkkenet.
Nederst i tabel 5 ses resultatet af en måling, hvor luftrenseren er flyttet ind i soveværelset. Eksponeringen er i dette tilfælde kun 10 % af eksponeringen i dagligstuen, hvor cigaretrøgen blev genereret.

Konklusion og anbefalinger

Infiltrationer
Mange problemer med naborøg opstår, fordi mange ældre etageejendomme er blevet mere tætte udadtil. Herved reduceres udelufttilførslen gennem udeluftventiler, og en større andel af lufttilførslen til lejligheden tilføres via trappeskakte og lejlighedsskel.
Ved utætheder mellem lejlighederne udsættes beboerne for de omkringboendes lugte fra f.eks. madlavning, men værre er det, hvis naboen ryger.
Hovedformålet med undersøgelsen var at kvantificere overførslen af partikelforurening mellem nabolejligheder ved tobaksrygning. Resultaterne tyder på, at næsten 9 % af den mængde UFP-partikler, der genereres i kildelejligheden, infiltreres til eksponeringslejligheden (tabel 1).
Ved målinger med stearinlys under samme forhold som med tobaksrygning var resultatet 2-3 % (tabel 3). Forskellen skyldes måske at tobaksrøg og røg fra stearinlys har forskellige egenskaber.
Baggrundskoncentrationen af UFP var om natten 4,0E+09 p/m^3, og om dagen kan denne værdi stige til det dobbelte.
Resultaterne viser, at to cigaretter genererer en middelværdikoncentration på 22E+09 p/m^3 ▷

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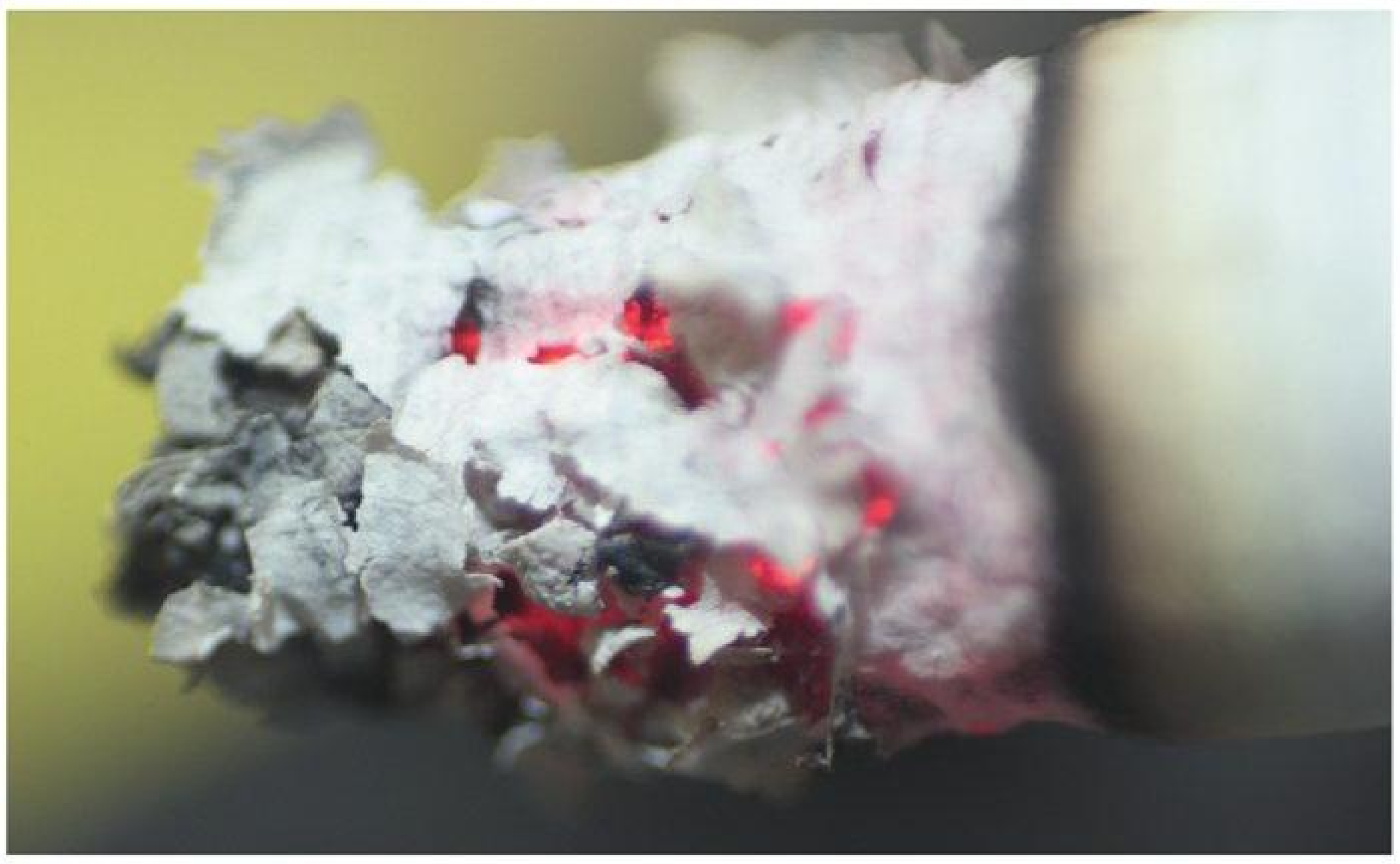
fra cigaretterne tændes, til koncentrationen aftager til samme niveau som baggrundskoncentrationen. Ved maks. værdi genereres 95,8E+09 p/m³.
Antages det, at 8,6 % af middelkoncentrationen på 22E+09 p/m³ infiltreres til nabolejligheden, modsvarer det en middelværdi på 1,9 E+09 p/m³, dvs. en forøgelse på 47 %. Ved beregning af maksimumværdien fås 8,2E+09 p/m³, hvilket svarer til en forøgelse på 205 % i forhold til baggrundskoncentrationen.
Infiltrationen fra kildelejligheden til eksponeringslejligheden var mindre i de renoverede bygninger - D og E - end i bygning A, der ikke var renoveret.



Løsningsforslag
UFP-koncentrationen i eksponeringslejligheden kan reduceres vha. tre metoder: kildekontrol, ventilation og rumluftrensning.

Kildekontrol
Røgfrie etageboliger eller røgfrie boligblokke er en af de afhjælpningsmetoder, der foreslås og er kendt i flere lande, bl.a. i Sverige, Canada, USA og Norge.
For at kunne gennemføre dette i almene boliger kræves en lovændring eller en dispensation fra Indenrigs- og Socialministeriet. Ifølge loven er det tilladt, at beboere ryger i deres egne lejligheder. Det kan derimod forbydes at ryge på fællesarealerne.
En anden afhjælpningsmetode er byggetekniske løsningsmodeller, dvs. en effektiv tætning af utætheder i bl.a. etageadskillelser via rørgennemføringer, vægge, revner og huller i gulv og tag, utætte murede ventilationskanaler, brevsprækker og utætheder omkring yderdøre.
Forskellige typer utætheder betyder, at hver etageblok, og måske hver lejlighed, kan kræve specielle tætningsmetoder.
I løbet af vinteren 2010 undersøges betydningen af tætning for overførsel af partikelforurening. Der gennemføres tæthedsmålinger for at vurdere lufttæthed af etageadskillelser mellem to lejligheder i en ældre etagebolig.

Ventilation
Ventilation reducerer vha. fortynding, koncentrationen af alle forureninger i en bygning og er derfor velegnet til at sikre et godt indeklima. Luft skal bevæge sig fra soveværelse og dagligstue til køkken og badeværelse og ud. Ved naturlig ventilation anvendes der ikke en ventilator til at suge luften ud fra lejlighederne. Ventilationen er bestemt af temperaturforskellen inde/ude og af vindpåvirkning af bygningen.
De ikke-renoverede bygninger havde et naturligt ventilationssystem. Luftskiftet i bygning A var 0,41 h^{-1} og i bygning B 0,74 h^{-1}. Ventilationens betydning for reduktion af UFP i eksponeringslejlighed og i kildelejlighed undersøges yderligere i vinteren 2010.

Rumluftrensning
Et virksomt middel til at reducere tobaksrøg i bygninger er lokal rensning af luften ved kildelejligheden eller eksponeringslejligheden. Det forudsætter, at der vælges tilstrækkelig stor kapacitet i forhold til ventilationen. Teknikken giver også mulighed for at reducere partikelniveauer i bygninger, hvor filtrering af tilluften mangler, dvs. bygninger med naturlig ventilation eller mekanisk udsugning. Ved valg af luftrenser er det vigtig at være opmærksom på sideeffekter som eksempelvis støj.
Tabel 2 viser beregnet infiltration af UFP fra kildelejlighed til eksponeringslejlighed i bygning A. Ved placering af en luftrenser i kildelejlighed, reduceres overførslen af UFP fra 8,6 % (uden luftrensere) til 5 % (med lufrensere). Resultatet viser også, at placering af en luftrenser i eksponeringslejligheden er lige så effektiv, som hvis luftrenseren havde været placeret i kildelejligheden. Ved brug af to luftrensere i eksponeringslejligheden, fordobles fjernelsen af UFP.
Tabel 4 og 5 viser, at den luftrenser, (CADR=100 m³/h), der blev brugt i denne undersøgelse, var effektiv nok til at kunne reducere eksponeringen fra cigaretrøg i kildelejligheden (volumen 110 m³) med 60-70 %. Ved brug af to luftrensere blev eksponeringen reduceret med 70-80 %. Effektiviteten øges yderligere, når luftrenseren placeres i det rum, hvor cigaretrøg genereres. Isolering af et kilderum i kildelejligheden har stor betydning for spredning af cigaretrøg til andre rum. Isoleringen antages at have tilsvarende betydning for rensning af luft i eksponeringslejligheden.

Anbefalinger

- Den mest effektive løsning er at fjerne forureningskilden.
- I kildelejligheder bør generering af forureninger ikke indebære spredning til andre lejligheder.
- Tobaksrygning bør ske i køkkenet med lukket dør og tændt udsugningsventilator/emhætte.
- Ved brug af luftrensere i kildelejligheder skal renseren placeres nær kilden for at opnå den største effekt. Udsugningsventilator skal være indstillet til maks. effekt.
- Luftmængden, som luftrenseren behandler, skal tilpasses ventilationen i lejligheden, hvor luftrenseren anbringes.
- De fleste luftrensere reducerer koncentrationen af partikler, mens koncentrationen af gasser kun reduceres i særlige luftrensere.

Tak

Der rettes en tak til de boligforeninger, der har hjulpet med at finde og udvælge bygninger og lejligheder til undersøgelserne. Projektet er gennemført med støtte fra Indenrigs- og Socialministeriet, Grundejernes Investeringsfond og Landsbyggefonden.

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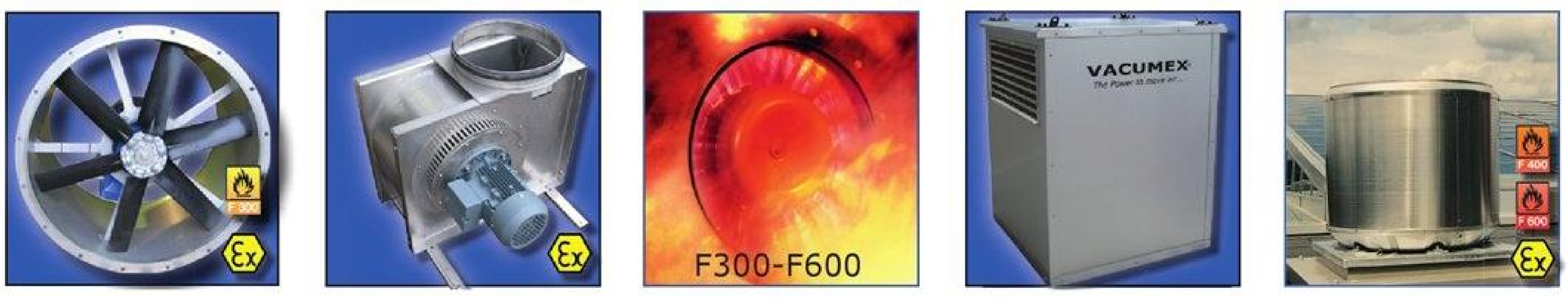

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Tekniske løsninger til reduktion af naborøg

Passiv rygning på grund af luftoverføring mellem lejligheder, såkaldt naborøg, er et vigtigt spørgsmål for beboere. Ingen ønsker at blive udsat for lugt og skadelige partikler fra andres tobaksrygning. Der er grunde til at antage, at problemet med naborøg især gælder ældre etageboliger. I denne artikel redegøres for undersøgelser af to tekniske løsninger

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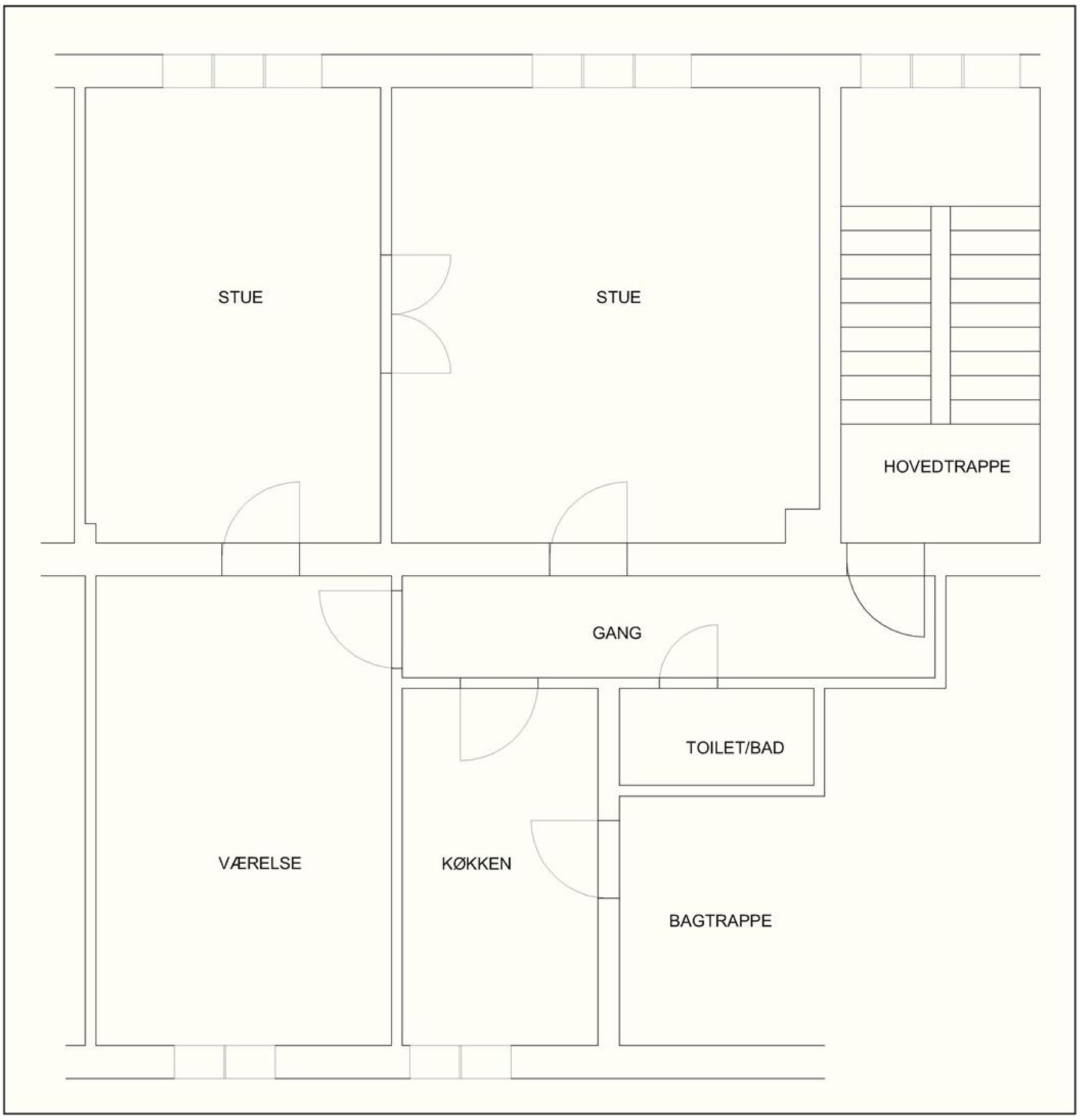
Der er forskellige måder, røgen kan sive fra én lejlighed til en anden. Det afhænger af bygningens ventilationssystem, konstruktion, tæthed og alder. Resultater fra projektets - *Tekniske løsninger til reduktion af eksponering for indendørs ultrafine partikler fra naborøg* - første fase viste, at i de mest kritiske tilfælde var overføringen af ultrafine partikler ca. ni pct. I det tilfælde lå eksponeringslejligheden over kildelejligheden. Kildelejligheden er lejligheden, hvori partiklerne genereres, mens eksponeringslejligheden er lejligheden, hvortil partiklerne fra kildelejligheden overføres.
Formålet med projektets anden fase er at identificere måder, hvorpå røg overføres fra én lejlighed til en anden samt at undersøge tekniske løsninger for at forebygge eller mindske overføringen af ultrafine partikler fra en kildelejlighed til en eksponeringslejlighed.
I denne artikel redegøres for undersøgelser af to tekniske løsninger. Den første er forsegling af gulvet i eksponeringslejligheden, og den anden er anvendelse af et nyt luftrensende kanalsystem (Photochemical Air Purification).
Undersøgelser af den første løsning blev gennemført i en lejlighed i en etageejendom fra ca. 1930. Pap og plastfolie af polyethylen blev anvendt til tætning af hele det eksisterende trægulv i eksponeringslejligheden. Resultatet af undersøgelserne viste, at efter tætningen var koncentrationen af partikler i eksponeringslejligheden uafhængig af genereringen af partikler i kildelejligheden.
Den anden løsning blev undersøgt under laboratorieforhold. Undersøgelserne viste, at systemets effektivitet med hensyn til fjernelse af partikler varierede fra ca. 30 pct. til 60 pct. efter 10 minutter, dvs. i den periode, hvor cigaretten var tændt.

Baggrund

Ikke-rygende personer, der bor ▷



Figur 1. Plan over eksponeringslejlighed.

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Tekniske løsninger... *Fortsat*

i etageboliger, er bekymrede, når uønskede gasser og partikler trænger ind i deres lejlighed fra rygende naboer [1]. I de senere år har undersøgelser peget på en mulig sammenhæng mellem udsættelse for ultrafine partikler (UFP) og menneskers sundhed [2].
Der er forskellige måder, hvorpå røg overføres fra én lejlighed til en anden. Det kan f.eks. være gennem stikkontakter, kabler eller telefonstik, rør-gennemføringer og revner i vægge og gulve.
Tidligere resultater viste, at i de mest kritiske tilfælde var overføringen af ultrafine partikler cirka ni pct., når eksponeringslejligheden lå over kildelejligheden. Overføringen af ultrafine partikler var en-to pct., når kildelejligheden var på samme etage som, eller over, eksponeringslejligheden. Desuden viste resultaterne, at med en aktiv luftrenser i kildelejligheden, reduceredes overførslen af ultrafine partikler fra ca. ni pct. (uden luftrensere) til ca. fem pct. (med luftrenser). Resultaterne viste også, at i eksponeringslejligheden er effekten af luftrenseren uafhængig af, om den anbringes i eksponeringslejligheden eller i kildelejligheden.

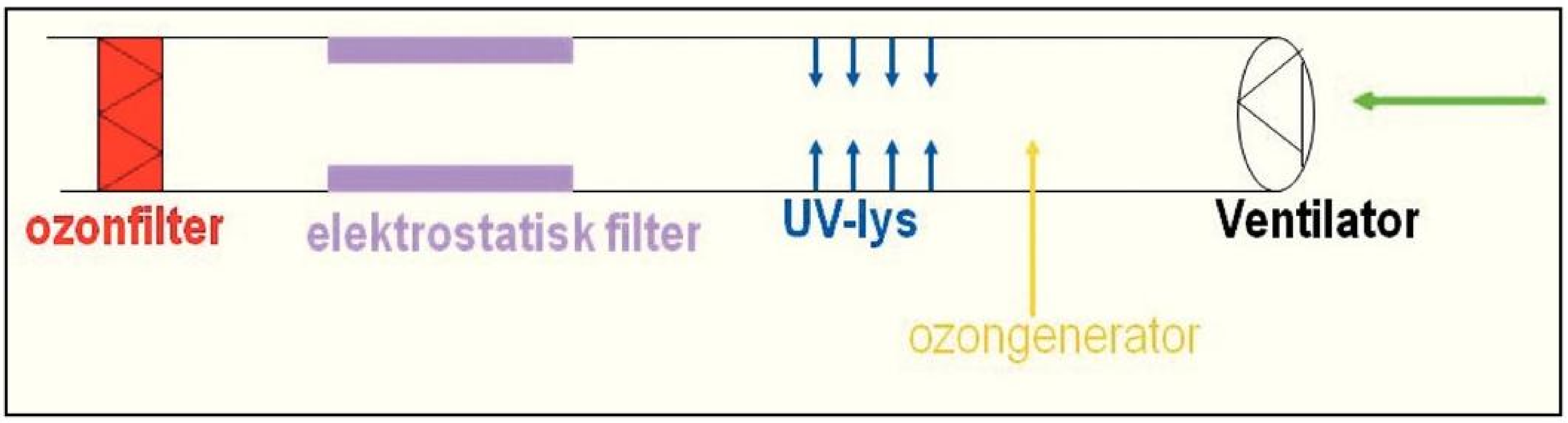
Figur 2. Tætning af eksponeringslejligheden.

Undersøgelsen, der beskrives i det følgende, har som formål at identificere, hvordan røg kan overføres fra én lejlighed til et anden samt at undersøge to tekniske løsninger til at forebygge eller reducere overføring af ultrafine partikler fra en kildelejlighed til en eksponeringslejlighed.

Metoder

Identifikation af spredningsveje og tætningsløsninger

Undersøgelsen blev gennemført i en femetagers karrébygning fra ca. 1930.. Kildelejligheden var beboet mens eksponeringslejligheden var ubeboet. Eksponeringslejligheden lå umiddelbart over kildelejligheden. Undersøgelsen blev gennemført i vinteren 2010, hvor ingen indendørs aktiviteter fandt sted i lejlighederne i løbet af målingerne.
Figur 1 viser lejlighedsplan for eksponeringslejligheden. Lejligheden består af to stuer (en suite) mod befærdet vej, et værelse og køkken mod gård, kombineret bad og toilet samt mellemgang. I lejligheden er gulvet blotlagt til lakeret trægulv i de to stuer og i værelset. I mellemgangen og i køkkenet er gulvet belagt med vinyl. I køkkenet er der køkkenskabe langs én væg. I bad/toilet er der betonplade. Mellem gulv og væg i stuerne, værelset og mellemgangen er ca. 150 mm fodpanel med fejeliste. Der er opsat radiator under vinduerne i stuerne og værelse. Varmerør er ført gennem gulvet ved lysning i værelse og i en stue. Varmerør for en stue er ført gennem skillevæg mellem stuer. Lofter antages at være forskallingsbrædder med rørvæv og puds. Mellem loft og væg er stuk. Midt på loftet i stuer og værelse er loftroset med eludtag. Der er aftræk i køkken og bad. I begge stuer er der udeluftventiler i ydervæggen. Desuden er vinduerne forsynet med udeluftventiler. Lejlighedens gulvareal er 64 m2, og volumen er 173 m3. Kildelejligheden er tilsvarende opbygget
Identifikation af spredningsveje blev udført ved hjælp af tæthedsmåling i eksponeringslejligheden før og efter tætning af lejligheden. Tætningen, se figur 2, blev gennemført på følgende måde: Indgangsdør fra hovedtrappen lukkes og brevsprække lukkes indefra med tape. Køkkendør til køkkentrappe samt dør mod bad/toilette lukkes og tapes. Alle vinduer og alle friskluftventiler lukkes. Aftrækskanal i køkken lukkes med ballon. Øvrige døre i lejligheden åbnes. På det blotlagte trægulv udlægges en gulvfiltpap (500 g/m2). Gulvpappen tilskæres ved fejeliste og føres over trin mellem stue og værelse. Samlinger stødes og tapes med 50 mm crepetape. Efterfølgende udlægges CE-mærket 0,2 mm polyetylenfolie. Folien føres op ad fodpanel og fastgøres til væg lige over fodpanel med enkeltklæbende crepetape. Ved dørtrin tapes folien til anslag. Ved rørgennemføringer for varmerør tapes.
Tæthedsmålingen udføres i henhold til DS/EN 13829, dvs. ved såvel over- som undertryk. Til undersøgelsen anvendes en Blower Door, som opsættes midlertidigt i det fuldt åbne køkkenvindue. Inde- og udetemperatur samt vindhastighed måles med termoanemometer. Foruden tæthedsmåling blev der foretaget en termografisk undersøgelse i henhold til DS/EN 13187, dvs. ved 50 Pa undertryk. Der benyttes et infrarødt kamera med høj opløsning og termisk sensitivitet på < 0,08 0C. Afkølede overflader og typiske utætheder registreres med termografiske billeder og simultant med digitale billeder. Ved de områder, hvor den termografiske undersøgelse viser tegn på utæthed, foretages stik- ▷



Figur 3. Luftrensende kanalsystem.

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▷ Tekniske løsninger... *Fortsat*

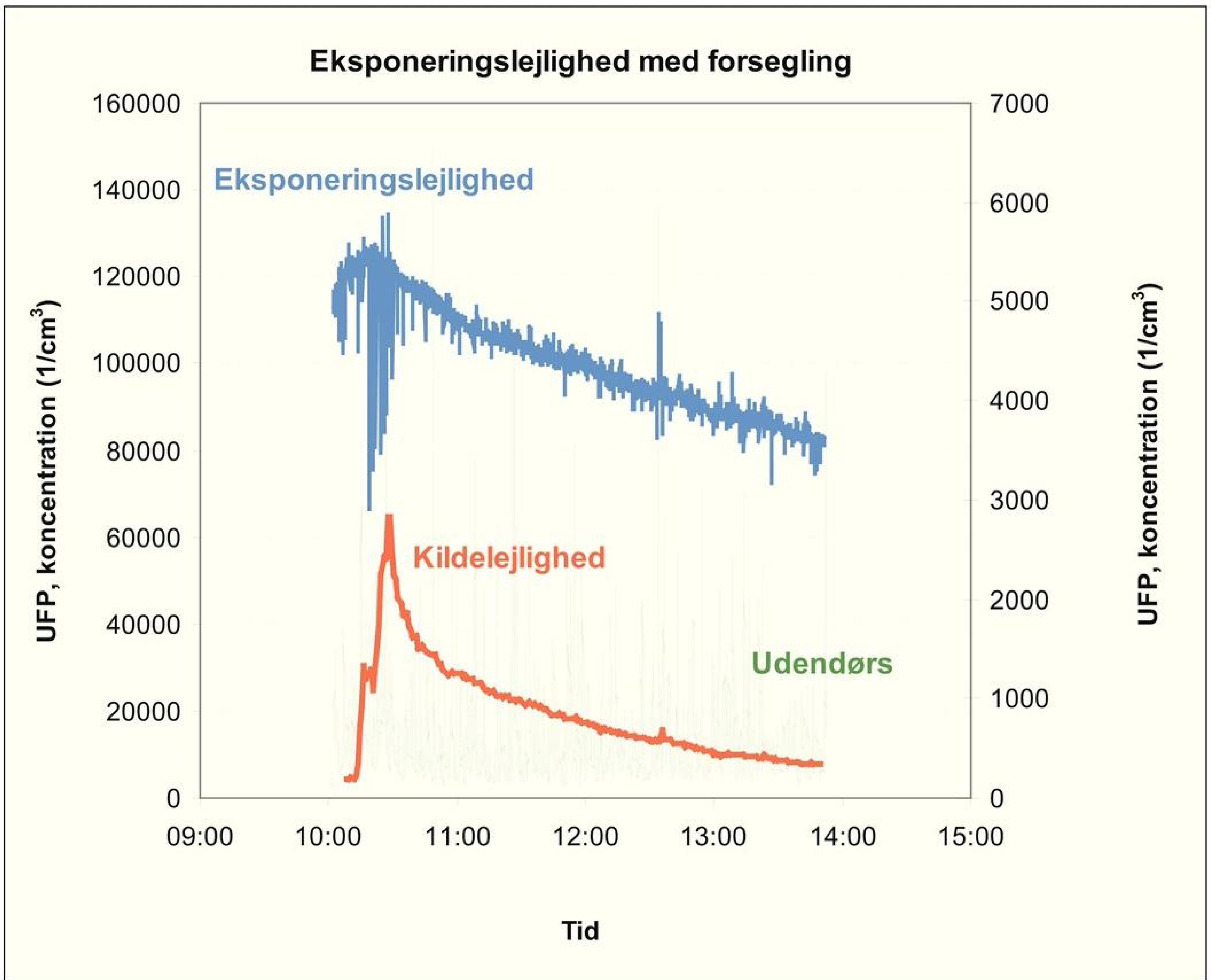
	Luftstrøm gennem utætheder			
	(Med tætn.)	(Med tætn.)	(Uden tætn.)	(Uden tætn.)
Enheder	l/s ved 50 Pa	l/(s, m^2) ved 50 Pa	l/s ved 50 Pa	l/(s, m^2) ved 50 Pa
Overtryk	342 (± 0.5%)	5.34	405 (± 0.5%)	6.32
Undertryk	319 (± 0.5%)	4.99	361 (± 0.5%)	5.65
Middelværder	330.5	5.17	383	5.99

Tabel 1. Tæthedsmålinger i eksponeringslejligheden med og uden tætning.

prøvekontrol med lufthastighedsmåler.
Kilder til generering af partikler bestod af to cigaretter, som blev placeret i kildelejligheden. Koncentrationer af ultrafine partikler blev målt simultant i tre forskellige positioner - i kildelejligheden, i eksponeringslejligheden og udendørs. Partikeltællerne var TSI model P-trak 8025 (2 stk.) og TSI model CPC 3007. I begge lejligheder blev der endvidere målt luftskifte, CO2, temperatur- og luftfugtighed over en periode på en uge. Også udeluftens temperatur og fugtighed blev målt.

Ydeevnemåling af luftrensende kanalsystem
En anden potentiel løsning til reduktion af koncentrationen af ultrafine partikler fra cigaretrøg er et luftrensende kanalsystem. Systemet blev undersøgt i laboratoriet under kontrollerede forhold. Systemet omfatter en luftrenserenhed, se figur 3, som består af otte UV-lamper, en ozongenerator, et elektrostatisk filter og et ozonfilter. For at undersøge virkningen af de forskellige dele i enheden, blev der gennemført seks scenarier. Scenarierne er beskrevet nedenfor.
Koncentrationer af ultrafine partikler og TVOC blev målt ved luftrenserenhedens indblæsning og udsugning. En tændt cigaret blev anvendt som partikel- og TVOC-kilde. Koncentrationer af ultrafine partikler blev målt ved hjælp af to kondenspartikeltællere, dvs. TSI model P-Trak 8025 og TSI model CPC 3007. Koncentrationerne af TVOC blev målt ved hjælp af to gasanalysatorer, Innova type 1312 og Brüel & Kjær type 1302.

- Scenario 1: Luftrenserenheden i drift som tiltænkt.
- Scenario 2: Luftrenserenheden i drift som tiltænkt i de første 10 minutter, mens cigaretten brændte. Derefter blev luftrenserens ozongenerator slukket, indtil UFP-koncentrationen havde nået sit oprindelige niveau (baggrundsniveau), hvorefter den blev tændt igen.
- Scenario 3: Luftrenserenheden i drift som tiltænkt i de første 10 minutter, mens cigaretten brændte. Derefter blev luftrenserens ultraviolette lys slukket, indtil UFP-koncentrationen nåede sit oprindelige niveau (baggrundsniveau), hvorefter den blev tændt igen.
- Scenario 4: Luftrenserenheden i drift som tiltænkt i de første 10 minutter, mens cigaretten brændte, hvorefter luftrenserens elektrostatiske filter blev slukket.
- Scenario 5: Luftrenserenheden i drift som tiltænkt, dog var det elektrostatiske filter slukket fra begyndelsen til slutningen af målingen.
- Scenario 6: Luftrenserenheden i drift som tiltænkt, dog var det elektrostatiske filter og ozongeneratoren slukket fra begyndelsen af målingen. Efter at cigaretten var brændt ud, og koncentrationen af partikler nåede sit oprindelige niveau, blev der tændt for det elektrostatiske filter og ozongeneratoren.



Figur 4. Målt koncentration af ultrafine partikler i kildelejlighed, eksponeringslejlighed og ude efter tætning gulvet af eksponeringslejligheden.

Resultater

Identifikation af spredningsveje og tætningsløsninger
Tabel 1 viser resultaterne af tæthedsmålingerne i eksponeringslejligheden med og uden tætning. Resultaterne viser, at tætningen reducerer luftstrømmen med 16 pct.
Koncentration af ultrafine partikler blev målt i kildelejligheden, i eksponeringslejligheden og udendørs før gulvet i eksponeringslejligheden blev forseglet. Beregninger viser, at overføringen af ultrafine partikler fra kildelejlighed til eksponeringslejlighed var omkring en pct. ▷

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▷ **Tekniske løsninger... *Fortsat***

Figur 4 viser koncentrationsforløbet af ultrafine partikler i kildelejligheden, i eksponeringslejligheden og ude efter tætning af gulvet i eksponeringslejligheden. Overføringen af partikler mellem de to lejligheder er beregnet efter en massebalancemodel, der tidligere er anvendt til analyse af partikelkoncentrationer [3]. Det er forudsat, at der er fuldstændig opblanding i eksponeringslejligheden, således at udsugningsluftens partikelkoncentration er lig med rumluftens partikelkoncentration. Resultatet af beregningerne er, at overføringen af ultrafine partikler fra kildelejlighed til eksponeringslejlighed ikke var signifikant, mens cigaretten (kilden) brændte i kildelejligheden.
Termograferingen i eksponeringslejligheden med og uden tætning viser, at der generelt er mange utætheder, særligt ved bjælkelagets anlæg i facaden, men også langs fodpaneler og i gulvets fer/not-samlinger. Især ved fodpanelerne er der mange utætte føringslister for kontakter og bøsninger for rør-gennemføringer. Ligeledes ses utætheder ved gennemføringer, ved skorstene og ved loftsroset.

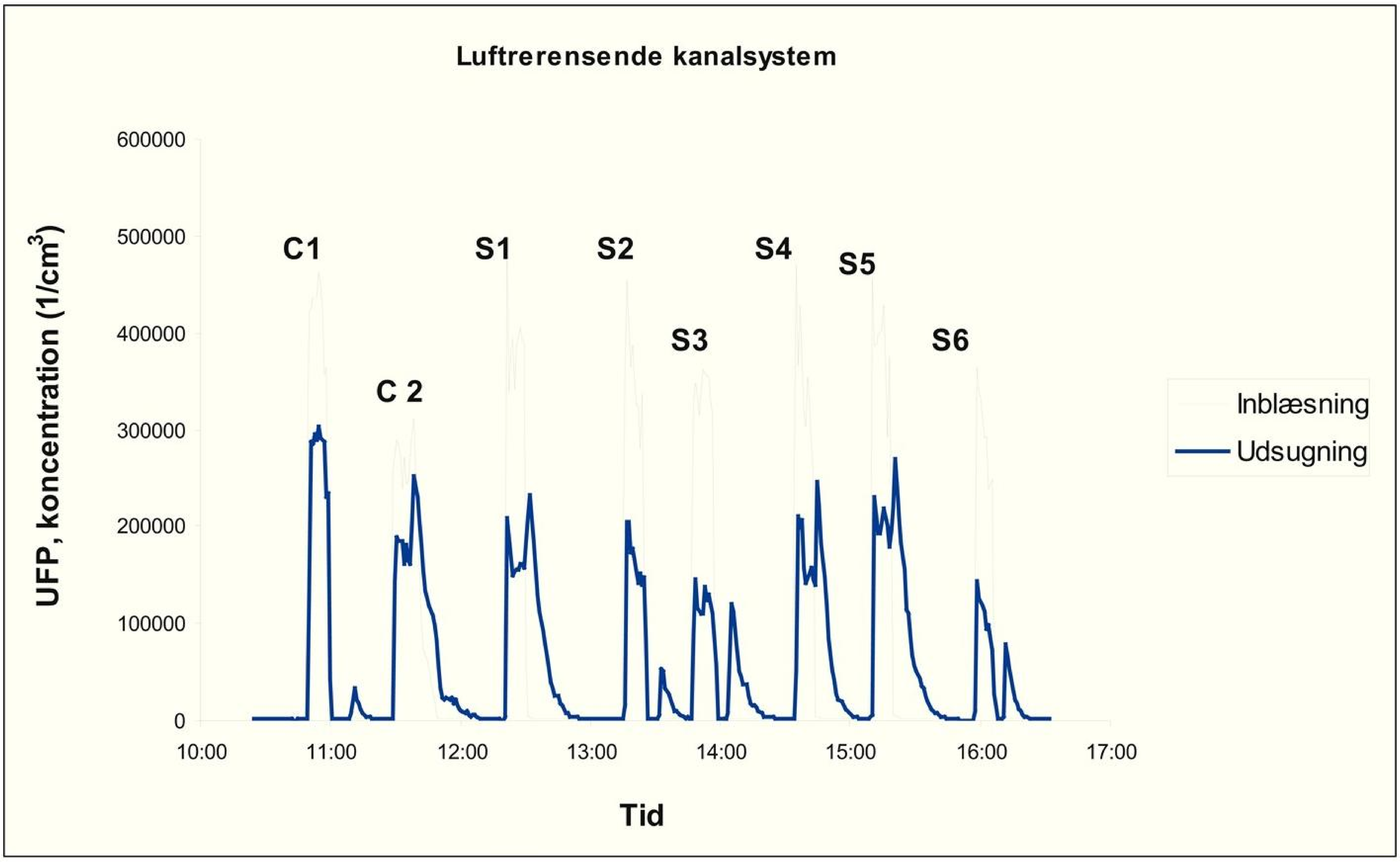
Ydeevnemåling af luftrensende kanalsystem
Figur 5 illustrerer forløbet af målte koncentrationer af ultrafine partikler ved luftrensningsenhedens indblæsning og udsugning. C1 betyder kalibrering af alle instrumenter i indblæsningsluften af luftrensningsenheden, herunder to kondensationspartikeltællere og to TVOC instrumenter. C2 betyder kalibrering af alle instrumenter i udsugningsluften af luftrensningsenheden. Kalibreringerne blev brugt til at beregne koncentrationerne af ultrafine partikler og TVOC. S1 til S6 står for Scenario 1 til Scenario 6, som beskrevet tidligere. Resultaterne af målingerne af TVOC-koncentrationerne havde et mønster, der svarede til resultaterne af målingerne af partikelkoncentrationerne.

Diskussion

Identifikation af spredningsveje og tætningsløsninger
Overføring af luft mellem to lejligheder i en etagebygning afhænger af ventilationssystem, konstruktion, tæthed og bygningens alder. Bygning som er undersøgt i dette projekt var naturlig ventileret.
Resultaterne af tæthedsmålingerne med og uden tætning af eksponeringslejligheden viste, at tætning af gulvet reducerer luftoverføringen med 16 pct.
Resultaterne af målingerne af partikelkoncentrationerne viser, at overføring af ultrafine partikler fra kildelejlighed til eksponeringslejlighed var omkring en pct., når gulvet i eksponeringslejligheden ikke var forseglet. Figur 4 viser de målte koncentrationsforløb i kildelejlighed, eksponeringslejlighed og udendørs efter tætning af gulvet i eksponeringslejligheden.
Efter at gulvet i eksponeringslejligheden blev forseglet, observeredes ingen stigning af partikelkoncentrationen i eksponeringslejligheden i forbindelse med partikelgenerering i kildelejligheden. Der kan tænkes flere forklaringer, som ydermere kan kombineres, på det observerede: Én er, at etageadskillelsen mellem kildelejligheden og eksponeringslejligheden var forholdsvis tæt allerede inden tætning; overføringen af partikler var lav (en pct.). En anden forklaring kunne være, at overføringen til eksponeringslejligheden reduceres ved, at partikler adsorberes i tætningsmaterialerne. En tredje forklaring kunne være, at overførte partikler deponeres på plastoverfladerne i eksponeringslejligheden.

Ydeevnemåling af luftrensende kanalsystem

Øgede krav til energieffektivitet ▷



Figur 5. Målte partikelkoncentrationer i luftrensningsenheden indblæsning og udsugning.

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▷ Tekniske løsninger... *Fortsat*

Scenario	Beregnet tilbageholdelse af ultrafine partikler (%)
S1: Alle dele arbejder kontinuerligt	40
S2: Slukket ozongenerator efter afbrænding af en cigaret	45
S3: Slukket UV-lys efter afbrænding af en cigaret	59
S4: Slukket elektrostatisk filter efter afbrænding af en cigaret	47
S5: Slukket elektrostatisk filter fra begyndelsen af målingen	30
S6: Slukket UV-lys og ozongenerator fra begyndelsen af målingen	60

Tabel 2. Beregning af tilbageholdelse af ultrafine partikler

gør det nødvendigt at undersøge mulighederne for at forbedre ventilationssystemer i boliger. En forbedringsmulighed er at udvikle behovsstyrede ventilationssystemer til boliger. En anden tekniske løsning kunne være luftrensende kanalsystemer. For at afklare i hvilket omfang en sådan teknisk løsning er brugbar, testedes en ny luftrensnings-teknologi i et kanalsystem.

Den første kolonne i tabel 2 er en kort beskrivelse af de forskellige scenarier. Den anden kolonne i tabel 2 viser beregnede tilbageholdelsesgrader af ultrafine partikler. I alle scenarier var en cigaret placeret ved indgangen af systemet. Cigaretten blev efterladt brændende i 10 minutter.

Tilbageholdelsesgraden af ultrafine partikler i procent i tabel 2 blev beregnet ved at subtrahere det beregnede areal under kurven i figur 4 for indblæsningskoncentration, og det beregnede areal under kurven for udsugningskoncentration og derefter dividere med det beregnede areal under kurven for indblæsningskoncentration, ganget med 100.

Resultaterne fra scenario 1 til scenario 4, som havde samme betingelser, de første 10 minutter, viste, at tilbageholdelsesgraden af ultrafine partikler varierede mellem ca. 30 pct. og 60 pct. efter 10 minutter, dvs. når cigaretten var brændt ud.

I scenario 5, hvor det elektrostatiske filter var slukket fra begyndelsen, var tilbageholdelsesgraden ca. 30 pct., og i scenario 6, hvor både det elektrostatiske filter og ozongeneratoren var slukket fra begyndelsen ca. 60 pct.

Desuden viste resultaterne fra scenario 2 og scenario 3, at når ozongeneratoren og UV-lyset blev tændt, øgedes koncentrationen af ultrafine partikler igen. Samme fænomen opstod i scenario 6, da det elektrostatiske filter blev tændt igen. Årsagen er, at cigaretrøg genererer både partikler og kemiske stoffer i systemet.

I løbet af de første 10 minutter kan en del kemiske stoffer være blevet adsorberet på overfladen af kanalsystemet, da luftstrømmen og den medtransporterede ozon ikke var i stand til at fjerne alle kemiske stoffer. Dette kan forklares ved, at ozonet, der tilføres systemet, reagerer med de kemiske stoffer, som adsorberes i kanalsystemet og skaber nye ultrafine partikler. Samme fænomen forekom, når UV-lyset blev tændt igen, da UV-lys bidrager med en del af ozonet i kanalsystemet. Endelig konklusion nødvendiggør yderligere undersøgelser for at bekræfte disse resultater.

Konklusion

Tætningsundersøgelsen viste, at der var mange utætheder i eksponerings-lejligheden. De fleste utætheder forekom i overgangen mellem væg og gulv. Der forekom også optrængning gennem gulvet. Resultaterne af tæthedsmålingerne med og uden tætning af gulvet viste, at tætning reducerer overføringen med 16 pct.

Der er vigtige udviklingspotentialer i metoden, men den skal udvikles og afprøves yderligere, før det er muligt at anbefale metoden.

Resultaterne fra det luftrensende kanalsystem med luftrenser viste, at tilbageholdelsesgraden af ultrafine partikler varierede mellem ca. 30 pct. og 60 pct. Luftrenserteknologien er stadig under udvikling for at forbedre systemets ydeevne og den praktiske anvendelse i indeklimaet. Derudover er det nødvendig at foretage detaljerede undersøgelser af teknologier baseret på anvendelse af UV-lamper, ozongenerator, elektrostatisk filter og ozonfilter for at sikre systemets funktionssikkerhed.

Projektet er gennemført med støtte fra Indenrigs- og Socialministeriet, Grundejernes Investeringsfond og Landsbyggefonden. Tæthedsmålinger er foretaget af Bygge- og Miljøteknik A/S.

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The effectiveness of portable air cleaners against tobacco smoke in multi-zone residential environments

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SUMMARY

The purpose of this study was to investigate how the effectiveness of portable air cleaners (ACs) against tobacco smoke is influenced by the clean air delivery rate (CADR), the location of the AC in relation to the pollution source and the apartment structure. The study was based on field experiments and simulations with the CONTAM software. The AC effectiveness was about 80% for one AC, and 93% for two ACs in the studied apartment (volume=110m^3). Ultrafine particles (UFP) exposure in a room without tobacco smoking (clean room) could be much less than in the source room if these rooms were not directly connected with each other (but indirectly connected via doors open to other rooms). Operating the AC in one of the rooms without cigarette smoking could develop a partly isolated clean environment. However, this led to a rather low cleaning effectiveness for the concentration of ultrafine particles in the apartment as a whole. If operating the AC in the room where cigarettes are being smoked, the UFP exposure in the whole apartment can be further reduced.

INTRODUCTION

Environmental tobacco smoke (ETS) exposure relates to an increased risk of many adverse health effects, including lung cancer, asthma onset and exacerbation and acute respiratory illness [1]. In Denmark, about 20% of deaths among adults aged >35 years are due to tobacco smoking [2]. Although tobacco smoking is banned in public places, it appears that children are still at risk of high exposure to secondhand tobacco smoke (SHS) in their home [3, 4]. Therefore, controlling ETS exposure in residential buildings is important to protect smokers' families, especially their children. However, the ventilation rates in residential buildings are generally too small to efficiently remove the tobacco smoking particles (the average air change rate for all studied apartments was 0.48h^{-1}). For residential buildings, especially those with natural ventilation, implementation of room air cleaners may be convenient and effective to control indoor air pollutants. However, the clean air delivery rate of the air cleaners, the relative location of the air cleaner to the pollution source and the apartment structure, as well as the indoor air change rate, all affect the AC effectiveness.

The purpose of this study was to investigate the AC effectiveness against multi-zone tobacco smoke under different CADRs and different locations of the AC. Special attention was paid to the apartment structure and the influence of room dividing doors being open or closed.

METHODS

The field experiments were carried out in an apartment (see Figure 1) with natural ventilation.

The natural ventilation system had air inlets in the living room and bedroom, and air outlet chimneys in the kitchen and WC. The apartment entrance door and all windows were closed during experiments. Indoor and outdoor UFPs concentrations were measured by two condensation particle counters, and temperature and relative humidity were also monitored. A passive tracer gas method was used to measure the air change rate, infiltration from outdoors and air transfer between apartments. Two electrical ACs (each with CADR=240m^3/h according to the manufacturer) were used as air cleaning devices. The door between the bedroom and the living room (BL door) and the door to the kitchen (K door) were open or closed during different experiments. The other doors were open during all experiments. The cases of cigarette smoking and AC in the same room and in different rooms, keeping the BL door and K door either opened or closed, or using none, one or two ACs were studied. The AC was started at the same time as smoking started.

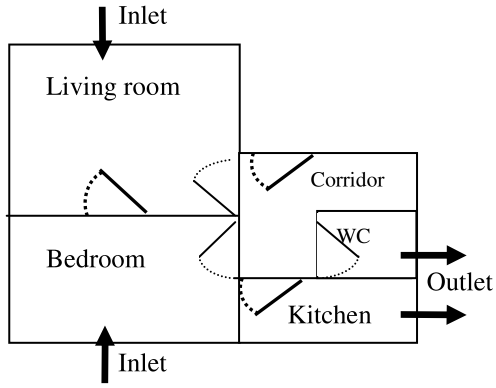

Figure 1. Configuration of the test apartment. The door between the bedroom and the living room is denoted BL door, and the door to the kitchen is denoted K door.

In an apartment, even small temperature differences between rooms can induce large inter-zonal air flows [5], which, furthermore, results in the smoking pollutants being well mixed between the zones. The multi-zone temperature differences were smaller than 2°C in all measured cases. Thus, in the CONTAM simulations the temperature differences (Δt) 0.1°C, 1°C and 2°C were applied according to the following relationship, $t_{bedroom}=t_{living\ room}+\Delta t=t_{corridor}+2\Delta t$. The agreement between measurement data and the simulation under the same environmental conditions was tested, and an example, shown in Figure 2, indicated a high degree of agreement between the CONTAM simulation and the measurements.

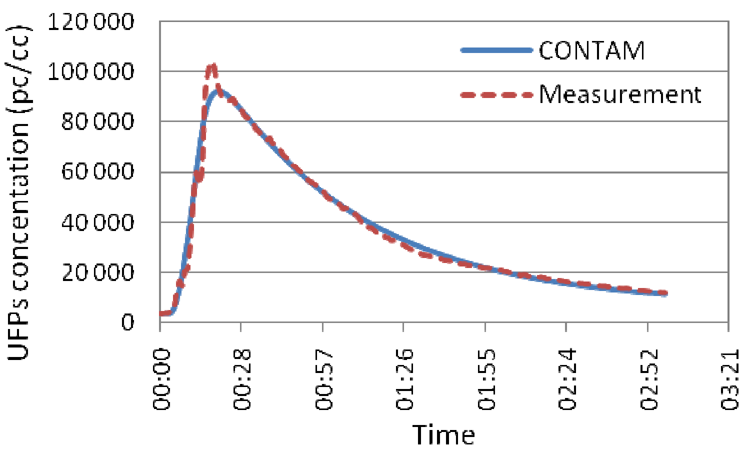

Figure 2. Comparison between CONTAM simulation results and measurement results.

RESULTS

1. Influence of apartment structure on the mixing of indoor particles

Indoor air distribution directly influenced the distribution of tobacco smoking pollutants and the AC effectiveness. Apartment structure, temperature differences between rooms and ventilation can all affect air distribution. Therefore, with the ventilation rate of the apartment kept constant, UFP distribution and AC effectiveness were studied for the following cases: open BL door (directly connecting the "clean" bedroom and the polluted living room - the source room) and closed BL door (the clean bedroom and the living room still being indirectly connected via the corridor), open K door and closed K door (isolating smoke pollutants in the source room – when smoking in the kitchen). CONTAM simulations of the above cases were carried out with multi-zone temperature differences of 0.1°C, 1°C and 2°C, according to the relationship given in the previous section.

1.1 Indoor air well mixed

Figure 3 shows the measured UFP concentrations for the case of keeping the BL door open, smoking 2 cigarettes in the living room and without any AC. The curves of UFP concentration in clean room (bedroom) and source room (living room) almost overlap each other, which mean that keeping the BL door open resulted in well mixed indoor air.

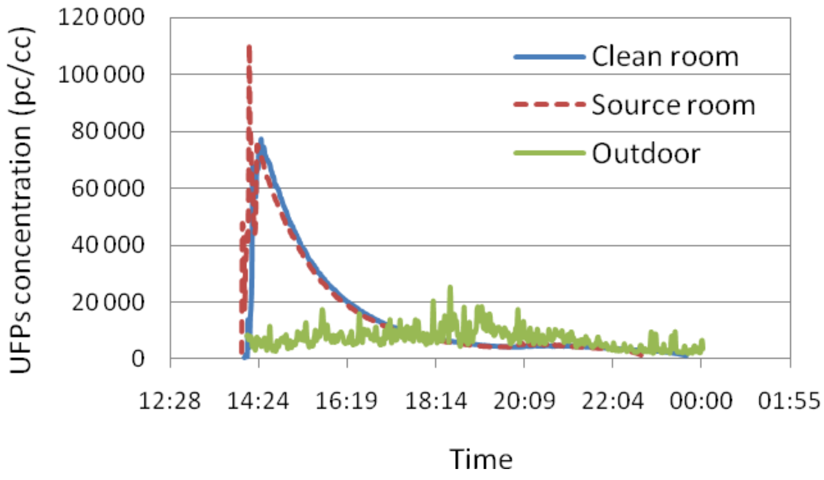

Figure 3. Indoor UFP concentrations for the indoor air well mixed case (BL door open).

1.2 Indoor air not well mixed

The measured UFP concentrations for the case of closed BL door, smoking 2 cigarettes in the living room and without AC in any room are shown in Figure 4. The different peak concentrations and a time delay are obvious between bedroom (clean room) and living room (source room), which means that keeping the BL door closed limited the spread of indoor tobacco smoking pollutants from the source room.

The above results are also shown in Figure 7. UFP exposures were about the same in the living room and in the bedroom if the BL door was open. Otherwise, the UFP exposure was lower in the bedroom than in the living room, when the BL door was closed, as expected.

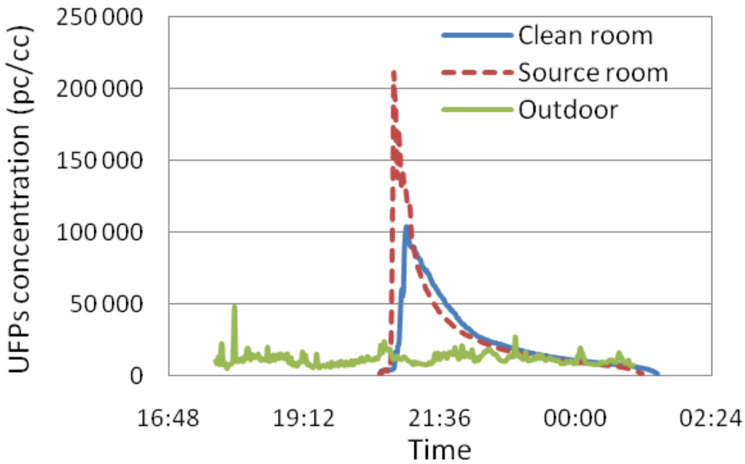

Figure 4. Indoor UFP concentrations for a not well mixed case (BL door closed).

Comparing Figure 3 and Figure 4, it can be seen that keeping the BL door opened or closed clearly influenced the UFP transport from the source room to the clean room. In other words, keeping the BL door closed, to some degree isolated UFPs from the source room to the clean room. The UFP exposure difference (S) between clean room and source room could be defined according to Equation 1, where $E_{cleanroom}$ is the UFP exposure in the clean room and $E_{sourceroom}$ is the UFP exposure in the source room.

$$S = 1 - \frac{E_{cleanroom}}{E_{sourceroom}} \tag{1}$$

The parameter S represents UFPs exposure isolation between the clean room and the source room. Larger S means that more pollutants are isolated from the clean room. The influence on S by the temperature difference between the rooms was simulated by CONTAM, and the results are shown, together with measurement, data in Figure 5. When the BL-door was closed, but the clean room and the source room indirectly connected, via open doors to the corridor, the UFP exposure could be somewhat less in the clean room than in the source room. The CONTAM simulations showed that, depending on the temperature difference, the exposure difference varied from 38% to 10% for the case without AC and 14% to -1% for the case with two ACs in the source room. The former figures mean that, without AC, when the multi-zone temperature difference was smaller than 0.1°C, the UFP exposure in the clean room was less than 62% of the exposure in the source room. But when the multi-zone temperature difference was increased to 1°C and 2 °C, the UFP exposure in the clean room was close to 90% of that in the source room. The negative value of S means that the UFP exposure in the source room was lower than that in the clean room, which occurred when two ACs were running in the source room.

In conclusion, indirect connection between the source room and the clean room partly isolates tobacco smoke UFP from the clean room. Furthermore, a smaller multi-zone temperature difference results in more UFPs being isolated. Additionally, although the apartment structure can to some degree isolate pollutants, the CADR should be chosen according to the whole apartment's volume to avoid low S values induced by large multi-zone temperature differences.

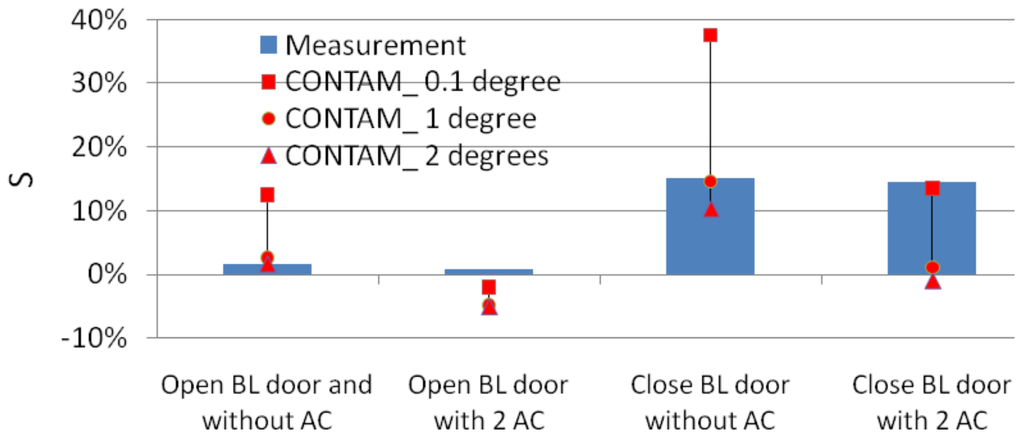

Figure 5. UFP exposure difference (S) between source room (living room) and clean room (bedroom). The ACs were located in the source room.

1.3 Indoor air isolated

In one case the pollutants were close to completely isolated, i.e. when smoking in the kitchen and keeping the K door closed. The results show that less than 3% of the UFPs infiltrated from the polluted kitchen to the bedroom (see Figure 6) regardless of whether an AC was in operation in the kitchen, or not. Thus, in this case the previously described S-value was higher than 97%. Therefore, an easy solution to SHS exposure appears to be smoking in kitchen while keeping the K door closed. With the K door open there was practically no difference between the exposure in the kitchen and in the bedroom, i.e. the S value is about 0%. This was most probably due to large temperature differences between the rooms.

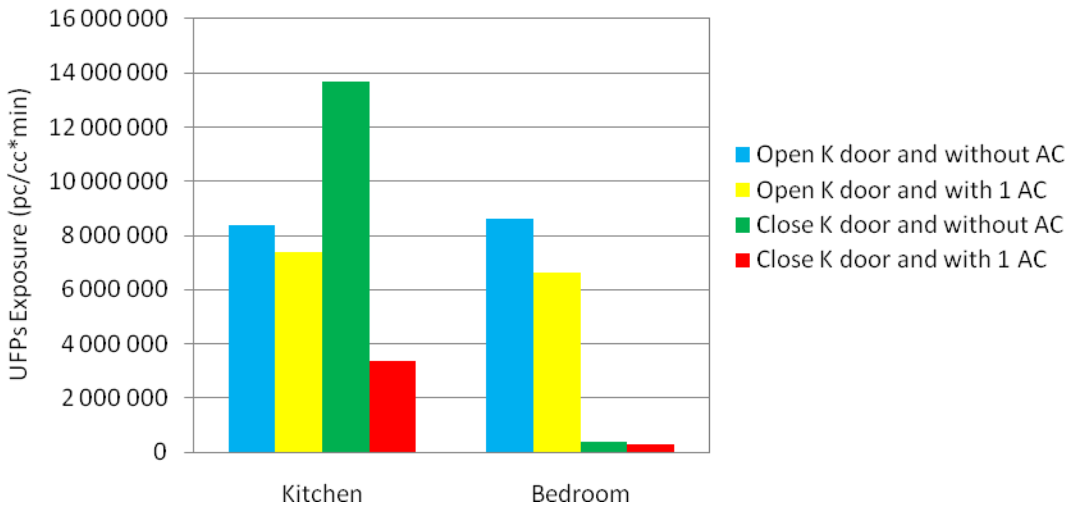

Figure 6. UFP exposure in kitchen and bedroom with open and closed kitchen (K) door. The AC was located in the kitchen. The source was located in the kitchen.

2. Air cleaner effectiveness H

The exposure in the kitchen was reduced by 76% by using one AC when keeping the K door closed; see the data in Figure 6. Similarly, the exposure in the living room was reduced by 64% by using one AC when keeping the BL door open; see the data in Figure 7. The kitchen was smaller than the living room and also isolated by the K door being closed, which explains the larger exposure reduction in the kitchen. Using one AC, the UFP personal exposure was reduced from $6.9 \cdot 10^6$ pc/cc·min to $2.5 \cdot 10^6$ pc/cc·min during a 3h period, when the BL door was open. Additional experiments showed that when two ACs were used, the exposure dropped to $2.1 \cdot 10^6$ pc/cc·min. The AC reduced the indoor UFP exposure close to the outdoor exposure level, see Figure 7. In the experiments, ambient UFP concentration was about 10^4pc/cc.

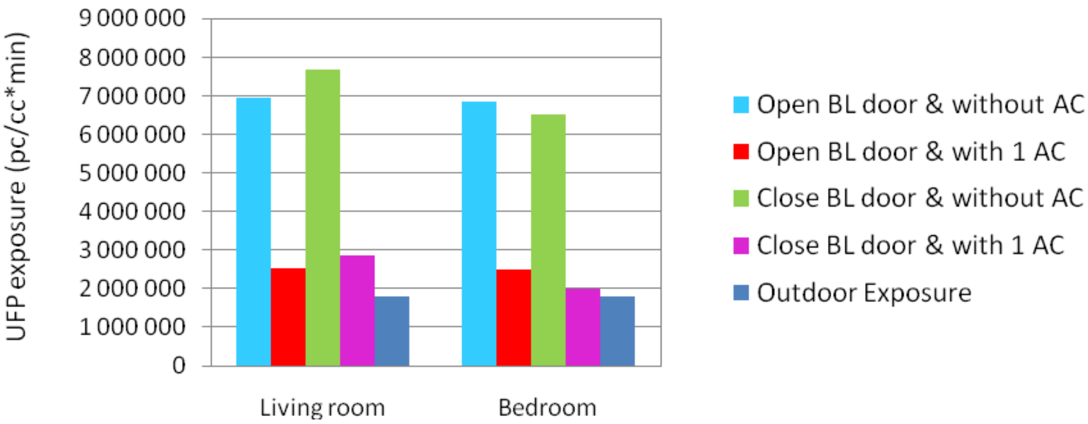

Figure 7. Indoor UFP exposure during 3 hours for the above cases. Source room = living room, clean room = bedroom. The AC was located in the living room.

For to these well-mixed cases, the AC effectiveness H in the whole apartment was calculated by Equation 2, which is defined by Miller-Leiden et al. [6]. Here, C_{ac} is the indoor concentration with AC; $C_{no\ ac}$ is the indoor concentration without AC. The effectiveness H for one AC and two ACs are shown in Figure 8.

$$H = 1 - \frac{C_{ac}}{C_{noac}} \quad (2)$$

The AC effectiveness under stable conditions was 80% for one AC, and 93% for two ACs; see Figure 8. Note that it took more than 1.5 h before steady-state conditions were reached. During this period the AC effectiveness, H, was substantially lower than the maximum value.

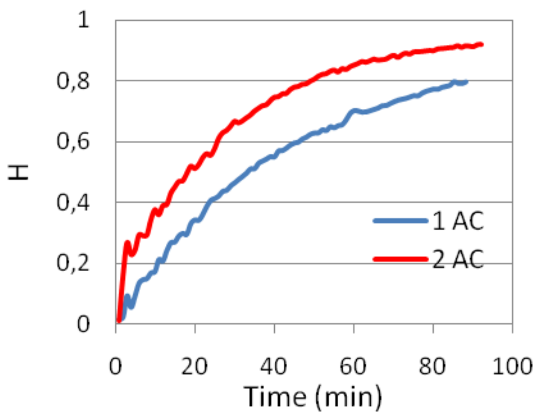

Figure 8. The air cleaner effectiveness H for one AC and two ACs

3. Influence of AC location relative to the pollution source

The relative location of AC to pollution source is another factor influencing UFP exposure. The UFP exposure reduction percentage (R) is defined by Equation 3, which evaluates UFP exposure reduction in one room by comparing UFP exposure with AC ($E_{with\ AC}$) and UFP exposure without AC ($E_{without\ AC}$).

$$R = 1 - \frac{E_{withAC}}{E_{withoutAC}} \quad (3)$$

Figure 9 shows values of R, calculated for the clean room (bedroom) and the source room (living room). Data are shown both for the case with two ACs located in the living room and for the case with two air cleaners located in the bedroom. The BL door was closed in all of the cases. Similar to the analysis of the parameter S, the influence of room temperature differences was also analyzed by CONTAM simulations. When tobacco smoking occurred in the living room, and two ACs were located in the bedroom, a relatively isolated clean environment was developed in the bedroom (R about 85% in the bedroom and 45% in the living room. This situation can be expected to result in a rather low cleaning effectiveness in the whole apartment regarding UFPs. While operating the AC in the source room (living room), the exposure-value in both the living room and in the bedroom was about 70%. It can be assumed that also all other rooms would show similar R-values, i.e. a rather large exposure reduction in the whole apartment.

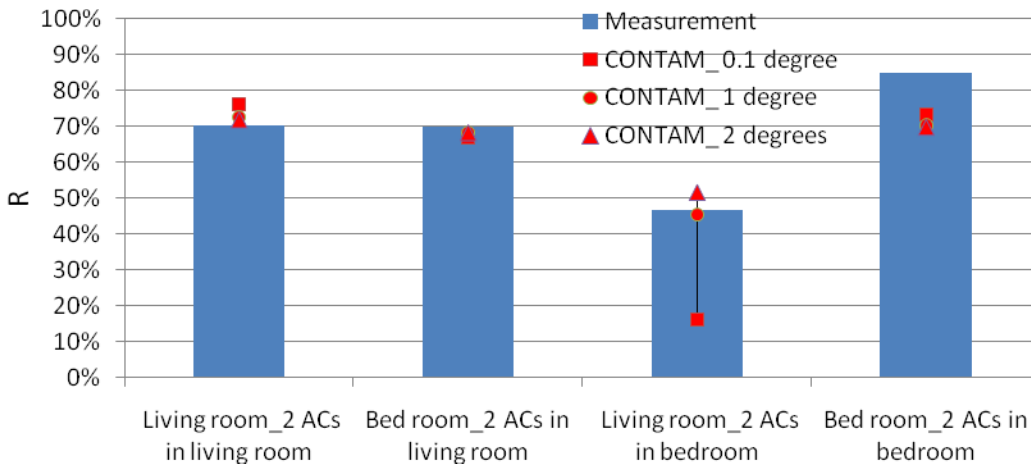

Figure 9. UFP-exposure reduction percentage (R) for different locations of the ACs

CONCLUSION

For this apartment ($V=110m^3$), one AC ($CADR=240m^3/h$) was, in most of the studied cases, enough to reduce the indoor UFP exposure by about 65%-75% in individual rooms. The highest exposure reduction, R=85%, was observed when two ACs were used in the bedroom when keeping the door between the bedroom and the living room closed.
The lowest exposure reduction, R=12%, was observed when using one AC in the kitchen and keeping the kitchen door open while smoking took place in the kitchen. Isolation of the

kitchen by keeping the door closed increased the exposure reduction obtained by the AC to 76%. In this case, when the kitchen door was closed, the exposure to smoke particles in non-smoking rooms was only a few percent of the exposure in the kitchen. When the kitchen door instead was left open, a massive spread of particles within the apartment was observed. The particle spread is due to large inter-zonal air flows induced by large temperature differences between rooms.
Although the apartment structure could, to some degree, isolate pollutants, the CADR should preferably be chosen according to the whole apartment's volume. Furthermore, the ACs should be placed in the same room as the strongest particle source. For example, operation of two ACs in the living room, where cigarettes were smoked, reduced the UFP exposure by about 70%, both in the source room and in the adjacent non-smoking bedroom. The total capacity of the two ACs corresponds to 4.4 air changes per hour, expressed as an average value for the entire apartment. This is about ten times the ventilation air change rate.

ACKNOWLEDGEMENT

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Quantification of ultrafine particles from second-hand tobacco smoke infiltration

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SUMMARY

This paper presents some of the results of a second-hand tobacco smoke intervention study carried out in 19 flats in four different buildings. Two of the investigated buildings were non-renovated and two others were renovated. The aim of the study was to quantify infiltration of ultrafine particles from a smoker's flat into a non-smoker's flat. In addition, several tests were carried out to describe some solutions for reduction of particle concentrations in the smoker's flat and the non-smoker's flat. The air change rates and the indoor particle concentrations were measured continuously during the measuring periods. The particle sources (particle generating activities) were cigarette-burning in the un-occupied buildings and candle-burning in the occupied buildings. Reductions of the concentration of ultrafine particles using air cleaning devices were studied. Results showed that the transfer of ultrafine particles was about 9% when the source flat was located below the receiving flat, whereas the transfer was 1-2% when the source flat was on the same floor as, or above, the receiving flat.

INTRODUCTION

Second-hand tobacco smoke (SHS) in flats is an emerging public issue in the Nordic countries, in particular in Denmark, where people spend approx. 16 h/day indoors [1]. Smoke can infiltrate a flat in various ways. The infiltration rate depends on the tightness of the building envelope and its design. A Danish study shows that window slits only replace 14% of the exhausted air; the rest comes from elsewhere in the building [2]. Some of the common openings where smoke seeps from a smoker's flat into a non-smoker's flat include electrical outlets, cable or phone jacks, pipes (plumbing), cracks in walls and floors, etc.

Numerous studies have documented the contribution of tobacco smoke to elevate the concentration of ultrafine and fine particles indoors [3]. During recent years investigations have indicated a possible association between exposure to ultrafine particles and human health [4].

Several studies show that the concentration of particles indoors may be reduced to a certain extent by means of ventilation or by filtration using portable or in-duct air cleaners [5]. However, the ventilation rate in residential buildings is generally not designed to remove particles and gases originating from smoking.

Most previous studies have focused on the quantification of particles from direct exposure to SHS. However, very few studies have examined quantification of particles from indirect exposure to SHS. Therefore the aim of the present study is quantification of ultrafine particles (UFP) from SHS infiltration in flats.

METHOD

The study was carried out in four different residential buildings. Two of the buildings (Buildings A and B) are of exactly the same type and design, they are approx. 70 years old and not renovated. The third building (Building C) is 100 years old and recently partially renovated, whereas the fourth building (Building D) is 140 years old and recently completely renovated. Four flats were included in the study in Building A and two flats in Buildings B, C and D, respectively. In each building the studied flat (Flat 2) was placed immediately above another flat (Flat 1).

Figure 1 illustrates a complete unit of flats for the present study. In Building A a complete unit was used. In Buildings B, C and D Flat 1 and Flat 2 were used.

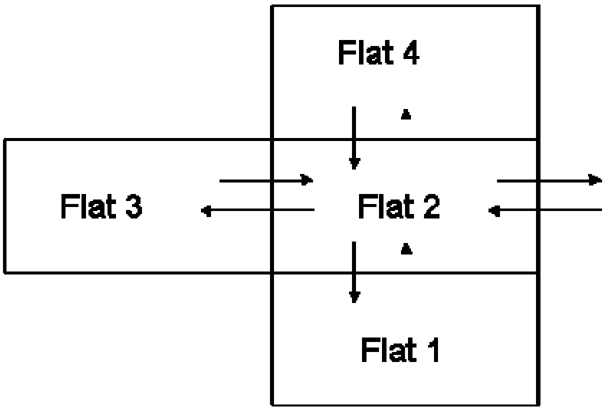

Figure 1. Sketch of a complete unit of flats.

Particles were generated in one flat and the infiltration of UFPs was measured in the flat above. The particle sources (particle generating activities) used in the source flats (Flat 1) was cigarette-burning in the un-occupied buildings (Buildings A) and candle-burning in the occupied buildings (Building C and D). Building B was an un-occupied building, which was used in both cases, i.e. cigarette-burning and candle-burning. Two cigarettes were burned for approx. 10 minutes each in the un-occupied flats and three pure wax candles were burned in the occupied flats.

The UFP concentrations were monitored by means of three condensation particle counters. One of the particle counters was placed in the source flat (Flat 1, where particles were generated), the second one in the exposure flat (Flat 2, which was infiltrated by particles from Flat 1) and the last one was used for sampling the outdoor concentration. Two of the particle counters were TSI model P-Trak 8025. The third one was a TSI model CPC 3007, which was used for measurements in the outdoor air.

The P-Trak 8525 instrument enabled real-time measurement of particle number concentration and data collection. The particle detection range of the instrument was between 0.02 and about 1.0 µm. The CPC 3007 was similar to the P-Trak 8525 with data recording in the diameter range from 0.01 to about 1 µm [6].

The PFT technique (Per Fluorocarbon Tracer) was used to measure air change rates, air infiltration and air exfiltration in the apartments. The technique is a multiple tracer-gas method based on passive sampling. CO_2, temperature and relative humidity were recorded during the experiments. Possible solutions, such as placement of one or two electrostatic air cleaners (AC; CADR=240m^3/h), were investigated for reduction of exposure concentration in Flat 1 and Flat 2.

RESULTS

Figure 2 illustrates an example of the measured concentration course for tobacco smoke in Flat 1 (source flat) and in Flat 2 (exposure flat). Two cigarettes were burned in Flat 1, one in the living room and one in the bedroom. Background concentration in Flat 2 was approx. 4.0E+09 p/m^3 during the night of the measurement.

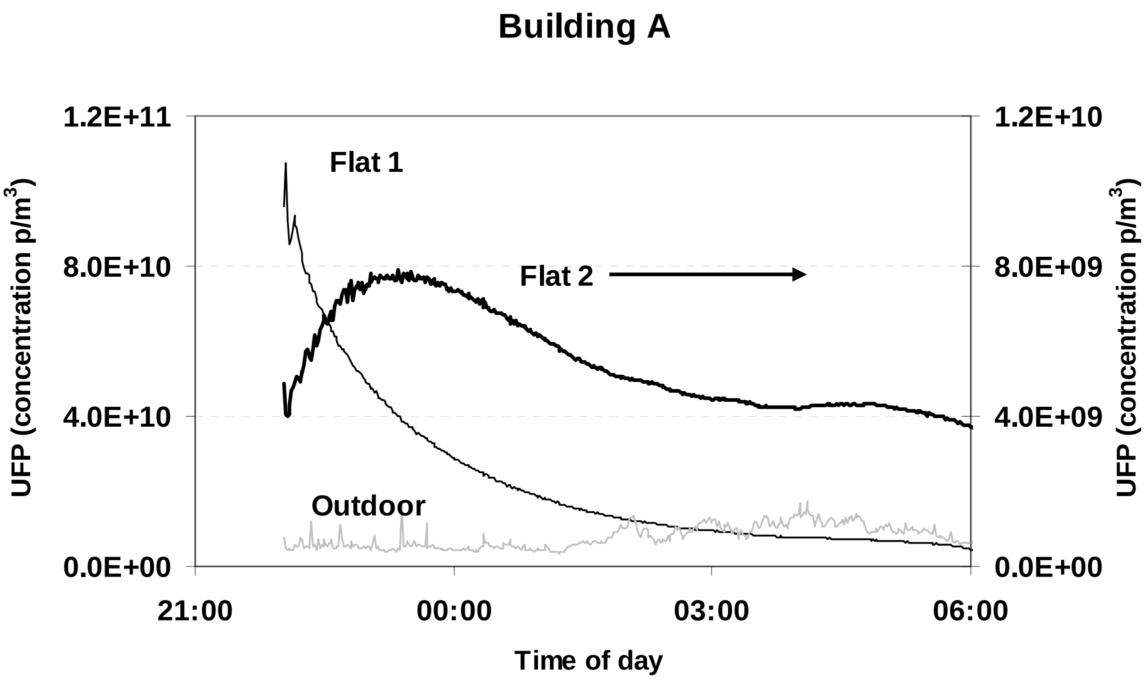

Figure 2. Measured concentration of UFP in Flats 1 and 2 and outdoors at Building A.

Figure 3 illustrates measured and calculated concentration of UFP in the exposure flat (Flat 2) in Building A. A mass balance model, previously applied to analysis of gaseous contaminant concentrations was used [7]. The basic assumptions that govern the model are that particles are perfectly mixed within Flat 2, i.e. the concentrations of particles are uniform throughout the whole volume.

$$c_{r(t)} = \frac{c_s \dot{V}}{\dot{V} + rV} + \frac{\dot{M}}{\dot{V} + rV} - \frac{\dot{V}}{\dot{V} + rV}\left[c_s + \frac{\dot{M}}{\dot{V}} - \frac{\dot{V} + rV}{\dot{V}} c_{r(0)}\right] e^{-\left[\frac{\dot{V}}{V} + r\right]\tau} \quad (1)$$

Where $\dot{V}$ = air flow rate (m^3/h), c_s = supply air concentration of UFP (p/m^3), c_r = air concentration of UFP in flat (p/m^3), V = flat volume (m^3), r =particle removal rate (1/h). $\dot{M}$ =

particle transfer from Flat 1 to Flat 2 ((p/m^3)*(m^3/h)). $\dot{M}$ was estimated by multiplying the UFP concentration in Flat 1 (the source flat) by the air leakage from Flat 1 to Flat 2.

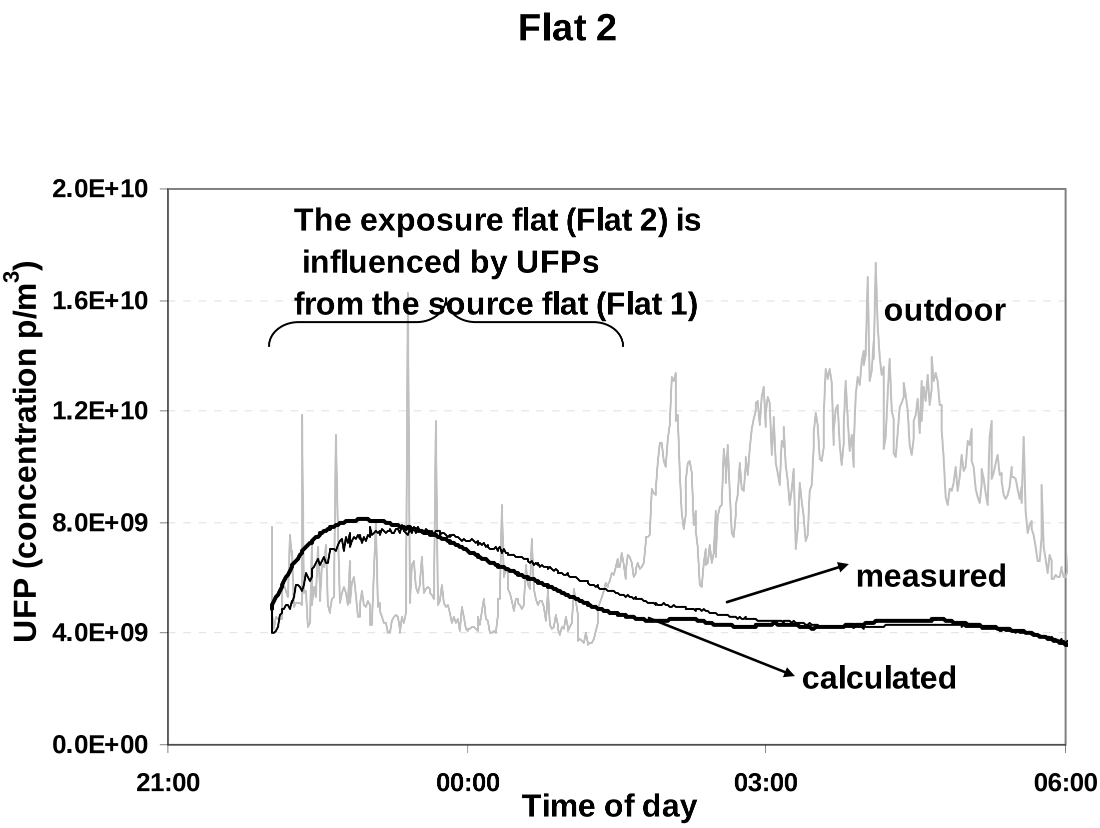

Figure 3. Results of measured and calculated of concentration of UFP in Flats 1 and 2 in Building A.

Tables 1 to 2 show the measured and calculated parameters of tobacco smoke in the exposure flat (Flat 2) in the Buildings A. Table 3 shows measured and calculated parameters for experiments with burning candles in Building B, C and D. It should be noted that Building B was a non-renovated building of exactly the same kind as Building A. Building C was recently partially renovated and Building D was recently completely renovated.

The second column in Tables 1 and 3 show the relative exposure in Flat 2, which means the percentage of UFP generated in Flat 1 that infiltrates Flat 2. The exposures in Flat 2 in Table 2 comprise infiltration inclusive reduction because of operation of the air cleaning devices.

The relative exposures in Flat 2 were obtained by expressing the total number of tobacco-related particles or candle related particles in Flat 2 as a percentage of the total number of particles measured in Flat 1 including background concentration. The total number of tobacco-related particles (or candle related particles) in Flat 2 was assessed as the area between two concentration curves calculated using equation 1. The first curve was calculated with consideration of particle transport by air leakage from Flat 1 to Flat 2. The second curve was calculated with the air leakage set to zero. Thus, the difference between these curves is an estimate of the particle transport from Flat 1 to Flat 2.

The third column shows removal rates of UFP in Flat 2. The removal rates are the sum of the deposition of particles on the inner surfaces of the rooms, removal by ventilation, and other sink mechanisms. The fourth column shows the air change rate in the Flat 2. The fifth column shows the air transfer due to leakage from Flat 1 to Flat 2. The air change rates and air transfer were set at weak mean values.

The rows 2 to 4 in Table 1 show data for successive experiments in Building A, where sources were placed in Flats 1, 4 and 3 respectively.

Table 1. Measured and calculated parameters of tobacco smoke in Flat 2 in Building A.

	Relative exposure(infiltration) in Flat 2 (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2	8.6	0.9	0.41	14
From Flat 4 to Flat 2	1.8	1.5	0.41	5
From Flat 3 to Flat 2	1.1	1.4	0.41	5

Another aim of the study was to describe to what extent air cleaner devices and the different states of renovation of buildings would affect the transfer of UFP between two flats.

Table 2 shows measured and calculated parameters of tobacco smoke in Flat 2 in Building A. The experiments were carried out in Flat 1 and Flat 2 in Building A. Colum 1 in Table 2 shows the location and number of air cleaners (AC) operated in Flat 1 and Flat 2.

Table 2. Measured and calculated parameters tobacco smoke in Flat 2 in Building A. With air cleaner (AC).

	Relative exposure (infiltration incl. reduction by AC operation)* (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2 1 AC in Flat 1	5.0	1.0	0.41	15
From Flat 1 to Flat 2 1 AC in Flat 2	4.2	1.9	0.41	15
From Flat 1 to Flat 2 2 ACs in Flat 2	2.6	3.9	0.41	16

Table 3 shows that the test with burning candles gave a relative exposure of 2.6% in Building B. This is about 1/3 of the value obtained with tobacco smoke in Building B, which gave a relative exposure of 7.1%. However, the tests with tobacco smoke in Building A and Building B showed similar results, see Table 1.

Table 3. Measured and calculated parameters of burned candles in Flat 2 in Building B, C and D.

	Relative exposure(infiltration) in Flat 2 (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2 Building B	2.6	2.7	0.74	10

From Flat 4 to Flat 2 Building C	0.3	4.4	0.92	2.3
From Flat 3 to Flat 2 Building D	0.7	1.5	0.36	5

DISCUSSION

There are various ways that smoke infiltrates from one flat to another. The air infiltration rate between two flats depends on the age, construction and tightness of the flat after renovation. A leaky flat exposes its occupants to pollution from surrounding flats, especially adjacent ones, and especially from smokers living in a flat below.

The results from the experiments in the two non-renovated buildings, A and B, indicated that 7-9% of the amount of UFP, generated by tobacco smoke in the source flat (Flat 1), infiltrated the flat located above (Flat 2), see Table 1.

The measurements with candle-burning in Building B, under the same test conditions as the tobacco smoke experiments, indicated an infiltration of 2-3% of UFP from Flat 1 to Flat 2, see Table 3. The difference in the infiltration rate of UFP has not been clarified but might depend on different characteristics of the particles generated by tobacco smoking compared with candle-burning.

It should be noted that the background concentration of UFP was 4.0E+09 p/m^3 during night time while it increased to approx. the double during day time.

The results from the example case (see Figures 1 and 2) showed that two cigarettes generated a mean value concentration of 2.2E+10 p/m^3 with a maximum concentration of 9.6E+10 p/m^3 in the source flat (Flat 1). The maximum concentration in the exposure flat (Flat 2) was somewhat less than 1/10 of that in Flat 1. The concentration declined to the background concentration after approx. 3 hours. Thus, occupants were exposed to a higher particle concentration compared with the background concentration during several hours.

Table 3 showed that the infiltration from the source flat (Flat 1) to the exposure flat (Flat 2) was lower in the renovated buildings, i.e. Buildings C and D compared with Buildings A and B which were non-renovated.

Technical solutions

The concentration of UFP in the exposure flat can be reduced by three different control methods; source control, ventilation control and use of portable air cleaning devices.

Source control: A smoke-free residential building is one of the remedial solutions suggested to private building owners, and it is known in several countries, including Sweden, Canada, USA and Norway.

In order to implement smoke-free residential buildings in public residential buildings, it is required to change the law or grant exemptions by the authorities. According to the law in Denmark, it is allowed to smoke tobacco in private homes.

Another method for reducing exposure to neighbour smoke is efficient sealing of the leaks in electrical outlets, cable or phone jacks, pipes (plumbing), cracks in walls and floors, etc. On the other hand different types of building construction and different types of leaks and cracks require different sealing methods. The results in the present paper shows that renovation of the buildings reduced the infiltration of UFP from the source flat to the exposure flat, see Table 3. However, the project also aims to study more in detail the sealing-effect on the transfer of tobacco smoke between two flats. This part will be carried out during the winter of 2010.

Ventilation control: Ventilation reduces the concentration of pollutants by means of dilution in order to ensure an adequate indoor air quality. Generally, the air in a flat should be supplied to the bedrooms and living rooms and exhaust should take place from the bathrooms and kitchen. In a non-renovated building, like Building A, the ventilation system was natural i.e. there was no fan to exhaust the particles from the flats. The amount of air that enters a building with natural ventilation depends on the wind and the thermal effects occurring within the building. The air change rate in Building A was 0.41 h^{-1} and in Building B 0.74 h^{-1}. This project also aims to find the ventilation effect on the transfer of the tobacco smoke between two flats. This part will be carried out during the winter of 2010.

Portable air cleaning devices: Portable room air cleaners can be used to clean the air in a polluted room when continuous and localised air cleaning is needed. For air cleaning devices to be effective, the capacity of the air cleaner must match the ventilation rate of the room. This cleaning technology is useful when there is no opportunity to clean the supply air by filtration, i.e. buildings with a natural ventilation system or with an exhaust ventilation system. Consumers should also consider possible side effects such as noise and ozone generation, when considering using air cleaning devices.

Measurement and calculation in Building A showed that, when one air cleaner was placed in the source flat, the relative exposure in the exposure flat (receiving flat) was reduced from 8.6% (without air cleaner) to 5% (with air cleaner). However, operating an air cleaner in the source flat will reduce the exposure in the source flat, and the exposure in the receiving flat can be expected to decrease accordingly. Thus, it was expected that the relative exposure (the ratio of the exposure increase in the receiving flat to the exposure in the source flat) should remain unchanged. The reason for the deviation has not been clarified. However, when using an air cleaner in the source flat the concentration varied rapidly. The peak concentration was reached after 9 minutes and decreased to 10% of the peak concentration within 1.4 h. Without an air cleaner in the source flat the concentration changed more slowly; the concentration decay to 10% of the peak value lasted about 5 h. It is not likely that the particles will have had the time to spread well between the rooms in the source flat so probably, when using an air cleaner in the source flat the source is mainly limited to one room. The measurement may therefore have lead to an overestimation of the exposure in the source flat, since the concentration was measured in the same room as where the tobacco smoke was generated. An overestimation of the exposure in the source flat will lead to an underestimation of the relative exposure in the receiving flat. In the case without air cleaner the measured particle concentration probably reflected the average concentration in the source flat more accurately, due to the much slower concentration changes.

When two air cleaners were placed in the exposure flat, a double removal of the UFP was recorded. However, theoretically, the marginal effect of the second air cleaner should be less than observed, a factor of around 1.5 rather than 2. The deviation between theory and measurements may partly depend on a change of the ventilation rate between the measurement series.

CONCLUSIONS

The results indicated that:

- In the non-renovated buildings between 1% and 9% of the UFPs generated by tobacco smoking infiltrated to a neighbouring flat.
- The transfer (infiltration) was highest (about 9%) when the source flat was located below the receiving flat.
- The transfer was less (1-2%) when the source flat was on the same floor as, or above, the receiving flat.
- The UFP-transfer was lower in the renovated buildings than in the non-renovated buildings.
- When one air cleaner was used in the receiving flat in one of the non-renovated buildings, the exposure to the neighbour’s tobacco smoke decreased from 9% to 4%. When using two air cleaners the exposure decreased further down to less than 3%.

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Technical solutions for reducing indoor residential exposures to ultrafine particles from second-hand cigarette smoke infiltration

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SUMMARY
An emerging public issue in Denmark is passive smoking in residential environments where non-smokers are exposed to harmful smoke from their neighbours. There are various ways that smoke infiltrates one flat from another. The air infiltration rate between two flats in a multi-storey building depends on the construction, tightness and age of the building. Earlier results from this project showed that, in the most critical cases, the transfer of ultrafine particles was about 9% when the source flat was located below the receiving flat. The purpose of the present study was to identify the ways in which smoke infiltrates from one flat to another and also to examine technical solutions for preventing or reducing infiltration of ultrafine particles from the source flat to the receiving flat. One of the technical solutions examined was sealing of the floor in the receiving flat. The study was carried out in the field in a multi-storey building and cardboard and plastic foil of polyethylene were used for sealing the entire wooden floor in the receiving flat. Another technical solution examined was a novel air circulating ductwork. The efficiency of the novel air circulating ductwork was examined by investigating the removal of ultrafine particles from a lit cigarette in a laboratory environment. The results showed that in the case where the receiving flat was sealed, the concentration of particles in the receiving flat was non-correlated with (or independent of) the emission of particles in the source flat. The test of the air circulating ductwork showed that the removal efficiency ranged from approx. 30% to 60% after 10 minutes, i.e. when the cigarette had burned out.

IMPLICATIONS
A number of non-smokers in residential buildings in Denmark are concerned that they may be exposed to gases and particles transferred from a neighbouring smoker. There is an urgent need for technical solutions that can reduce indoor exposures to ultrafine particles from second-hand tobacco smoke infiltration. This study proposed two technical solutions for reducing indoor ultrafine particle concentrations.

KEYWORDS
Second-hand smoke, cigarette, ultrafine particles, in-duct air cleaner, sealing

INTRODUCTION
Occupants living in multi-unit dwellings are worried when unwanted gases and particles infiltrate their flats from smoking neighbours. Second-hand cigarette smoke (SHS) and particle exposure in flats in multi-unit dwellings are considered harmful among non-smokers (Brink, and Clemmensen, 2007). During recent years investigations have indicated a possible relation between exposure to ultrafine particles (UFP) and human health (Bräuner, et al. 2007).

There are various ways in which smoke is transferred from one flat to another. Some of the common openings where smoke infiltrates from a smoker's flat to a non-smoker's flat include electrical outlets, cable or phone jacks, pipes (plumbing), cracks in walls, floors etc. The earlier results of this project showed that, in the most serious cases, the transfer of UFP was about 9% when the source flat was located below the receiving flat (Afshari et al. 2010). The transfer of UFP was 1-2% when the source flat was on the same floor as, or above, the receiving flat. In addition, the results also showed that when a single air cleaner was used in the receiving flat, the exposure to the neighbour's cigarette smoke decreased from 9% to 4%. When using two air cleaners, the exposure further decreased to below than 3%.

The aim of this study was to explain how smoke is transferred from one flat to another and also to examine two technical solutions for preventing or reducing infiltration of UFP from the source flat to the receiving flat.

METHODS

Identification of the ways of infiltration and sealing solutions

This part of the study was carried out in a residential building, which was 85 years old. The receiving flat (Flat 2) was placed immediately above the source flat (Flat 1). Flat 1 was occupied and Flat 2 was unoccupied. The study was conducted in the winter of 2010 while no other indoor activities took place in either of the flats during the measurements.

Identification of ways of air and smoke transfer were carried out using a fan pressurisation method (Blower door technique) in which a fan was used to create a steady-state pressure difference of 50 Pa across the envelope of Flat 2. The measurements were carried out before and after sealing of the floor of Flat 2. In order to measure the resultant airflow and pressure, Flat 2 was pressurised and subsequently depressurised. In addition, thermography was used when Flat 2 was depressurised. The entire wooden floor of the living room and two bedrooms of Flat 2 were sealed using cardboard (500 g/m^2) and plastic foil of polyethylene (0.2 mm). The plastic foil was pulled up above the skirting boards and attached to the wall by crepe tape. The floor of the hall and kitchen was already covered with Poly Vinyl Chloride (PVC), and therefore not with cardboard and plastic foil. The doors of the flats were closed and the letter box opening in the front door was sealed using crepe tape. All water traps in the kitchen, bathroom and toilet were filled with water.

In addition to the above-mentioned measurements, the transfer of UFP from Flat 1 to Flat 2 was quantified before and after sealing Flat 2. The air change rates and the indoor particle concentrations were measured continuously during the measuring periods. The particle sources (particle generating activities) were cigarette-burning in Flat 1. Two cigarettes were burned for approx. 10 minutes each in Flat 1. The UFP concentrations were monitored by means of three condensation particle counters (Afshari et al., 2010).

Air circulating ductwork

An air circulating ductwork was investigated in a laboratory environment as a possible solution for reducing exposure to UFP from cigarette smoke. The system consists of an ozone generator, 8 units emitting ultraviolet light (UV-light), an electrostatic precipitator and an ozone filter. In order to understand the effect of the different parts of the device for removing UFP, TVOC and ozone, 6 scenarios of measurements were carried out.

Scenario 1:The air cleaning device was used as it was designed to operate in the ductwork.
Scenario 2:The air cleaning device was used like in Scenario 1 during the first 10 minutes when the cigarette was burned. Then the ozone generator was turned off until the UFP concentration reached its initial level (background level) and then it was turned on again.
Scenario 3:The air cleaning device was used like in Scenario 1 during the first 10 minutes when the cigarette was burned. Then the ultraviolet lights were turned off until the UFP

concentration reached its initial level (background level) and it was turned on again. Scenario 4:The air cleaning device was used like in Scenario 1 during the first 10 minutes when a cigarette was burned, i.e. after approx. 10 minutes the electrostatic precipitator was turned off. Scenario 5: The air cleaning device was used like in Scenario 1, however in this scenario the electrostatic precipitator was turned off from the beginning to the end of the measurement. Scenario 6:The air cleaning device was used like in Scenario 1 with the exception that the UV-light and the ozone generator were turned off from the beginning of the measurement. When the cigarette was burned and the concentrations of particles reached its initial level, the UV-light and ozone generator were turned on.

The UFP concentration and TVOC were measured both in the supply air and the exhaust air of the air cleaning device. A burned cigarette was used as a source of particles and TVOC. The UFP concentrations were monitored by means of two condensation particle counters, i.e. TSI model P-Trak 8025. and TSI model CPC 3007. The concentrations of TVOC were monitored by means of two gas-analyser i.e. INNOVA type 1312 and Brüel & Kjær, type 1302.

RESULTS

Identification of the ways of infiltration and sealing solution

Table 1 shows the results of pressurising and depressurising Flat 2 with and without sealing.

Table 1. Airflow with fan pressurisation of Flat 2 with and without sealing.

	Airflow infiltration from Flat 1 to Flat 2 (with sealing)	Airflow infiltration from Flat 1 to Flat 2 (with sealing)	Airflow infiltration from Flat 1 to Flat 2 (without sealing)	Airflow infiltration from Flat 1 to Flat 2 (without sealing)
Units	l/s at 50 Pa	l/s, m^2 at 50 Pa	l/s at 50 Pa	l/s, m^2 at 50 Pa
Pressurising of Flat 2	342 (± 0.5%)	5.34	405 (± 0.5%)	6.32
Depressurising of Flat 2	319 (± 0.5%)	4.99	361 (± 0.9%)	5.65
Calculated average values	330.5	5.17	383	5.98

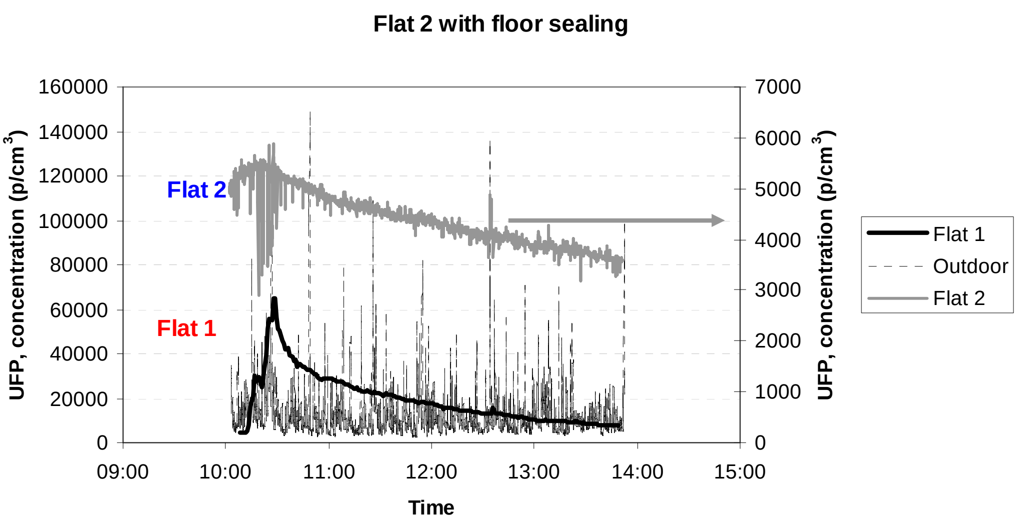

Figure 1. Measured UFP concentration in Flats 1 and 2 and outdoors after sealing the floor of Flat 2.

The results of the thermographic photos showed that there were many leakages in Flat 2. The leakages were paths to Flat 1 as well as to the outdoors. Most of the leakages were at the junction between walls and floors. There were also leakages through the floor of Flat 2.

The infiltration was calculated according to a mass balance model, previously applied to analysis of gaseous contaminant concentrations [3]. The basic assumptions governing the model are that particles are perfectly mixed within Flat 2, i.e. the concentrations of particles are uniform throughout the whole volume. The results of the measurements of particle concentrations showed that the UFP transfer was about 1% when Flat 2 was not sealed. In the case when Flat 2 was sealed, no increase of the concentration of particles in Flat 2 was detected.

Air circulating ductwork

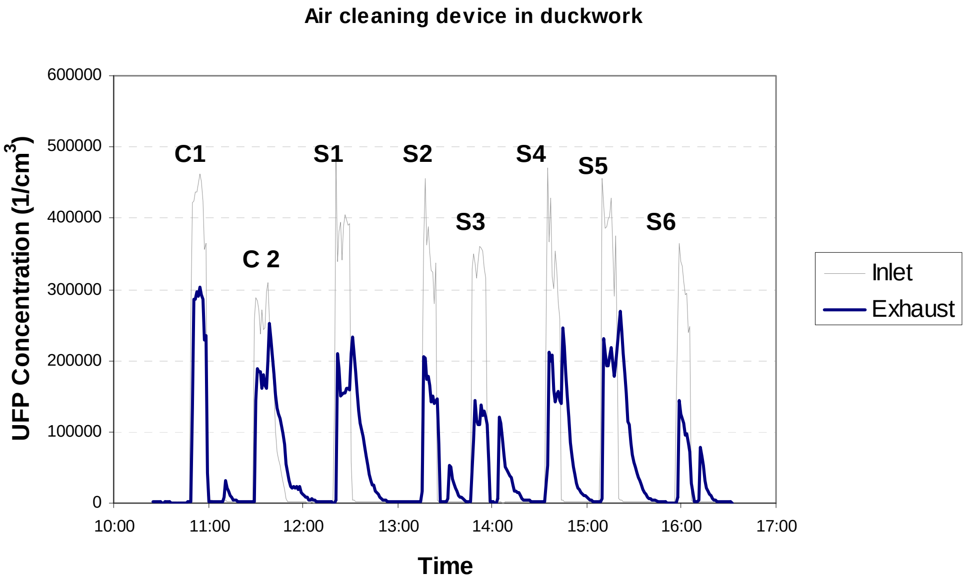

Figure 2. Measured UFP concentrations generated by cigarette in the inlet air and in the exhaust air of the air cleaning device.

Figure 2 illustrates the course of measured UFP concentrations of cigarette smoke in the inlet air and exhaust air of the air cleaning device tested in the laboratory environment. C1 means calibration of all instruments in the inlet air of the air cleaning device including two condensation particle counters and two TVOC instruments. C2 means calibration of all instruments in the exhaust air of the air cleaning device. The calibrations were used for calculating the concentration of UFP and TVOC. S1 to S7 stands for Scenario 1 to Scenario 7, described in detail above in section Methods. The results of TVOC concentrations showed a pattern similar to that of the UFP concentrations. The outdoor concentration was not measured, since it had the same influence on inlet and exhaust concentrations.

DISCUSSION

Air circulating ductwork

Ventilation reduces the concentration of pollutants by means of dilution. Generally, in a flat air should be supplied to bedrooms and living rooms and extract should be from bathrooms and kitchen. This can be effectively achieved if the building is equipped with a mechanical ventilation system. In Denmark the energy consumption for climatisation of buildings make up almost 40 % of the total energy consumption. One possibility of reducing energy consumption could be to enhance control of air-conditioning and ventilation rates in relation to the actual needs, i.e control-on-demand air handling system in residential buildings. A practical application is to investigate the possibility of using air recirculation together with air cleaners as a technical solution to improve IAQ while reducing the outdoor air supply and hence energy consumption for ventilation. In the present study a novel air cleaning technology was tested in a ductwork.

Table 2. Calculation of UFP removal efficiency from cigarette smoke.

Calculated UFP removal after burning a cigarette (%)	Scenarios explained
39.98	*S1*; All parts work continuously
44.99	*S2*; Turned off ozone generator after burning of a cigarette
58.67	*S3*; Turned off UV lights after burning of a cigarette
46.81	*S4*; Turned off electrostatic precipitator after burning of a cigarette
29.75	*S5*; Turned off electrostatic precipitator from the beginning of the measurement
60.04	*S6*; Turned off UV light and ozone generator from the beginning of the measurement

The air cleaning system consisted of four main parts, 8 ultraviolet lights, an ozone generator, an electrostatic precipitator and an ozone filter. In order to understand the effects of the different parts of the device for removing ultrafine particles (UFP), TVOC and ozone, 6 scenarios of measurements were carried out. Table 2 shows the calculation of UFP removal efficiencies of the cleaning system in 6 different scenarios. In all scenarios, a cigarette was placed at the inlet of the system and was left burning for 10 minutes. The second column in Table 2 shows the UFP removal efficiency after burning a cigarette, i.e. 10 minutes after the start of the measurement in each scenario.

The percentage of UFP removal efficiencies in Table 2 was calculated by subtracting the calculated area under the curve (Figure 1) for inlet concentration and the calculated area under the curve (Figure 1) for exhaust concentration, divided by the calculated area under the curve (Figure 1) for inlet concentration multiplied by 100. The results from Scenario 1 to Scenario 4, which had similar operation conditions during the first 10 minutes of the measurements, showed that the UFP removal efficiency ranged from approx. 30% to 60% after 10 minutes, i.e. when the cigarette had burned out. In Scenario 5 where the electrostatic precipitator was turned off from the beginning of the measurement, the UFP removal efficiency was approx. 30%. In Scenario 6, where both the UV-light and the ozone generator were turned off from the beginning of the measurement, the UFP removal efficiency was approx. 60%.

In addition, the results from Scenario 2 and Scenario 3 showed that when the ozone generator and the UV lights were turned on again the concentration of UFP increased. The same phenomenon was observed when the UV light was turned on again in Scenario 6. The reason was that cigarette smoke generated not only particles but also chemical substances in the system. During the first 10 minutes a lot of chemical substances might be adsorbed on the surfaces of the system, since the airflow and the supplied ozone were not able to remove all chemical substances. The ozone supplied to the system reacted with the chemical substances and generated new UFPs. The same phenomenon was seen in the case where UV light was turned on again, since the ozone photolysis by UV light leads to production of the hydroxyl radical OH and consequently leads to the removal of hydrocarbons from the air and also generation of UFPs. To clarify the phenomenon further investigations are needed in this research area.

Identification of the ways of infiltration and sealing solutions

In an old and non-renovated building, like the building in the present study, the ventilation system is based on natural ventilation i.e. there is no fan to extract the particles from the flats. There are various ways that smoke is transferred from one flat to another. The air transfer rate between two flats depends among other things on the age, construction and tightness of the flat. The results of the fan pressurisation method (Blower door) of Flat 2 with and without sealing showed that the sealing of the floor of Flat 2 reduced the infiltration by air by 16%. The results of the measurement of particle concentration showed that the transfer of UFP was about 1% when the source was located in Flat 1 and Flat 2 was not sealed. Figure 2 shows the UFP concentration in Flat 1, Flat 2 and the outdoor concentration. In the case where Flat 2 was sealed, the concentration of particles in Flat 2 did not increase. There could be three reasons why the UFP concentrations in Flat 2 did not increase. One possibility was that the infiltration of particles before sealing was only 1%. The second reason could be that the sealing materials on its own reduced the amount of particles that infiltrated Flat 1 from Flat 2. The third reason could be that the infiltrated particles to Flat 2 deposit on the plastic surface in the Flat 2.

CONCLUSIONS

The thermographic photos showed that there were many leakages in Flat 2. The leakages were paths to Flat 1 and to the outdoors. Most of the leakages occurred at the junction between walls and floors. There were also leakages through the floor of Flat 2. The fan pressurisation method (Blower door) of Flat 2 with and without sealing showed that the sealing of the floor of Flat 2 reduced the infiltration by the air by 16%. The test of air circulating ductwork showed that the UFP removal efficiency ranged from approx. 30% to 60% after 10 minutes, i.e. when the cigarette was burned. In addition the results showed that ozone generated by an ozone generator and UV light reacted with chemical substances adsorbed on the surfaces of the system and consequently generated ultrafine particles.

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