Indoor air quality in Nearly Zero Energy Buildings, reduction of exposure

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ABSTRACT

Various studies show a deterioration in indoor air quality after renovation and energy saving measures. NZEB dwellings are at the moment at an airtightness level, that the old slogan make buildings airtight and ventilate right is an very import solution for a good IAQ, but not without source control.
The first step in controlling indoor air quality is to avoid the emission of contaminants in the air such as, candles, cooking on gas and smoking. The second step is reduce the unavoidable harmful emissions by source control. For cooking fumes, a range hood is the most effective way to minimize the exposure. For $PM_{2.5}$ from ambient, filters can be applied in the mechanical supply of the ventilation system. Step 3 is a whole house ventilation system. With sufficient source control, the control of the ventilation system, can be smart, that means the ventilation only goes to a higher level because of odor control of human sources. Step 4 are stand-alone air purifiers, for cases where, the emissions of pollution cannot be reduced, e.g. in case of window airing. Based on literature an overview has been set up of examples of these steps and their effectiveness.
To estimate the combined effect of these measures on $PM_{2.5}$ exposure simulations with TRNFLOW/ COMIS have been executed. A 50 percentile emission pattern for $PM_{2.5}$ has been set up based on a year lasting monitoring with optical particle sensors in 100 Dutch dwellings. A cooker hood with 95% capture efficiency reduces the average exposure in the living room / kitchen with 51%. In combination with an F7 filter in the air supply the exposure in the living room is reduced with 82% in a NZEB dwelling. The combination of these two relative simple measures almost halves the total yearly exposure. This can be explained by the fact that the F7 filter not only cleans the air towards the kitchen/living room but also for the sleeping room in which relatively much time is spend.
A positive example of how to combine energy savings with a good indoor climate is through a performance contract or even a renovation as a service. The main air borne pollutant with regard to health for such a contract or service could be $PM_{2.5}$ and CO_2 could serve as an indicator for ventilation and odor control.

KEYWORDS

NZEB dwellings, IAQ, pollutants, PM 2,5

1 INTRODUCTION

Healthy indoor air can make or break the energy transition. Most people stay much longer inside than outside. Measurements show that indoor air in dwellings can be more polluted and hence less healthy than outside air due to indoor sources. With increasing insulation and airtightness, the importance of good and effective ventilation is a necessity. Living in a "airtight" building with stale air is not an attractive proposition.
On social media the discussion on health and energy savings has already started. Combining energy renovation with good and effective ventilation can improve the air quality. However, that does not happen automatically. Various studies show a deterioration in indoor air quality after renovation and energy saving measures. E.g. in a pre and post evolution of indoor air quality in retrofitted co-operative social housing (Broderick, 2017), concentrations of CO_2,

TVOC, and $PM_{2.5}$ significantly changed post-retrofit compared to post retrofit. Increases in pollutant concentrations were correlated with lower building air exchange rates post retrofit, although there was a positive impact on occupant comfort and building temperature. In Europe and various countries, there is a great deal of policy on energy saving in homes, and much less in the area of health and indoor air.
The big question is: “Which measures are reasonably possible and which reduction in exposure to harmful pollutants is possible, and how can we stimulate this?”

2 IAQ AND RELEVANT POLLUTANTS

Ventilation is not the only factor determining a healthy indoor air environment. Contaminant emission rates, absorption and desorption processes on building materials and furnishings and transport within building have similar effects. Aside indoor sources also outdoor sources play an important role. Exposures in homes of airborne pollutants contribute to 60 to 95% of our total lifetime exposure, and can create risks for acute health problems and for chronic diseases and can evaluated risk for premature death. (Borsboom 2016).
The main pollutants have outdoor origin, including for example combustion, traffic and agriculture. Examples of pollutants are particulate matter, ultrafine dust, soot, pollen, Radon, NOx and other combustion products.
The main sources of pollutants having indoors origin include humans (e.g. bio-effluents) and their activities related with hygiene (e.g. aerosol due to deodorant sprays), house cleaning (e.g. use of chlorinated and other cleaning products), food preparation (e.g. cooking particle emissions), building construction materials including furnishing and decoration materials (e.g. formaldehyde emissions from furnishings); tobacco smoking and combustion processes occurring indoors, as well as pets (e.g. allergens) (Borsboom 2016). Current ventilation solutions for dwellings are not designed to be a solution for all these contaminants. These ventilation solutions are mainly for the people in buildings.

In this article we will focus on Particulate Matter as this has the largest health impact (Logue, 2011).

2.1 Particulate matter

$PM_{2.5}$ in homes find their origin in for example unvented or improperly vented combustion and cooking in homes, aerosol product use and outdoor sources, physical sources and re-suspension of particles In the United States, Chan (2017) has measured 18 apartments over 14 days. The average indoor concentration of $PM_{2.5}$ was 18.6 µg/m^3. Large differences between the dwellings have been observed with regard to the average concentrations. At the same outdoor concentration (about 21 µg/m^3), the indoor concentration varied from 8.2 to 64.1 µg/m^3. A total of 836 particulate matter peaks were observed in the dwellings. Using an algorithm developed by them, an average $PM_{2.5}$ particulate emission of 30 mg per peak was determined. This algorithm was also used to calculate the contribution of particulate matter originating of indoor sources. This ranged from 15 to 85%. This means that 85% of the $PM_{2.5}$ was generated indoors in a number of homes.
The $PM_{2.5}$ fraction of particulate matter in the indoor environment of Dutch homes has been studied to a limited extent so far. In an exploratory study in 9 homes, Jacobs (2017) measured with optical particle counters during a week. These measurements showed that a large part of the fine dust is related to cooking activities. The participants in the study were instructed to take photos of the hob with their smart phone during cooking. This made it possible to link

increased particulate matter concentrations, "particulate matter peaks", to cooking. In addition, other non-cooking-related unknown peaks were also visible. At the end of the measurements, the origin of almost all peaks was determined in consultation with the participants. The maximum concentrations with respect to the various sources are shown in Table 1.

Table 1: maximum concentrations of $PM_{2.5}$ particulate matter in 9 Dutch homes (Jacobs, 2017)

Cooking	Concentration (μg/m^3)
Cooking	2000
Hair spray	140
Deodorant spray	350
Outdoor fireworks	75
Candles	40
Children playing	35
Recoil of smoke from a stove	35
Fire pit in the back garden	50

3 INVENTORY OF MEASURES TO IMPROVE INDOOR AIR QUALITY

3.1 The role of ventilation

Ventilation is in the first place to produce fresh air for occupants by diluting body odours and contaminants. Carbon dioxide is often used as a marker for ventilation. Carbon dioxide is produced by humans through exhalation. A concentration level of about 1200 ppm leads to an odour level that for many people is acceptable. Carbon dioxide is not a contaminant that at normal levels can be seen as harmful. At higher concentrations several studies show negative effects on the ability to concentrate and on the productivity of people. Dilution is not an effective ventilation strategy to reduce occupant exposure for most other contaminants.
The first step in controlling indoor air quality is to avoid the emission of contaminants in the air such as, candles, combustion products due to cooking on gas, smoking and minimizing emissions from building materials and furniture.
The second step is reduce the unavoidable harmful emissions by source control. For indoor sources as cooking fumes, a range hood is the most effective way to minimize the exposure (see 3.2). Another option is to prevent the spreading of contaminants in between rooms, for instance daycare products should be used in a room with an extract, in the so called wet rooms. For $PM_{2.5}$ from ambient, filters can be applied in the mechanical supply of the ventilation system.
Step 3 is a whole house ventilation system. With sufficient source control, the control of the ventilation system, can be smart, that means the ventilation only goes to a higher level because of odor control of human sources.
Step 4 are stand-alone air purifiers. In some cases, the emissions of pollution cannot be reduced. For example, because the resident likes to have the window open while the outside air is polluted. In such cases, a stand-alone air purifier can help reduce exposure.

3.2 Overview of measures

Table 2 gives an overview of reported effects of measures to improve air quality in homes based on these steps. The measures are prioritized along the principles of prevention and control strategies. Measures which eliminate the source are most effective, followed by local exhaust and supply ventilation and filtering. The least effective measure is dilution by mixing ventilation. Also the complexity of the measures is estimated. Most measures have a low complexity, which means that they can be installed by the resident themselves. In the literature only the cost effectivity for filtering is mentioned. Placement or improvement of air filters in the ventilation system or placement of stand-alone air cleaners both have a cost effectiveness of more than a factor of 10 (Fisk, 2017). This means that the health benefit expressed in euros is a factor of ten as large as the costs of the measure.

Table 2: reported effects of measures (*cost effectivity, **2476 MJ/year additional energy use).

Contaminant	Type	Measure	Effect	Com-plexity	Literature ref.
PM2.5 by smoking	Elimination	Stop with smoking inside	100%	Low	
NO2 gas cooking	Elimination	Electric cooking	100%	Middle	
PM2.5	Elimination	LED candles and tea lights	100%	Low	
PM2.5, soot	Elimination	No use of fireplace or wood stove	100%	Low	
Phthalates	Elimination	Removal of PVC flooring in bedrooms	?	Middle	Shu 2014
PM2.5 due to frying	Local exhaust	Hood 95 dm3/s, cooking on front burners Hood 83 dm3/s, cooking of 4 Dutch meals Hood 83 dm3/s, not covering front burners Hood 21 dm3/s (Dutch Building Code) Hood 21 dm3/s, not covering front burners	75% > 93% 70% 50% 25%	Middle Middle Middle Low Low	Singer 2012 O'Leary 2019 VentKook, 2018
NO2 gas cooking	Local exhaust ventilation	Hood with exhaust to ambient	67%	Middle	Logue 2014
PM2.5 frying	Local exhaust & Filtering	Recirculation hood	< 30%	Low	Jacobs, 2017
PM2.5	Filtering & local supply	HEPA filters in breathing zone asthmatic	99%	Low	Fisk 2013
PM2.5	Filtering	Enhancement filter quality in US home air heating and cooling systems Placement of stand-alone HEPA filters	> 10* > 10*	Low Low	Fisk 2017
PM2.5	Filtering	Enhancement filter quality ventilation supply (relative to outdoors)	> 97%	Low	Singer 2017
PM2.5	Filtering	Air cleaners in 8 intervention studies	40 – 60%	Low	Day 2018
PM2.5	Filtering	Ozone generating air cleaners	negative	Low	Waring 2008
PM2.5	Filtering	HEPA filter on vacuum cleaner	99%	Low	Lioy 1999
PM2.5	Ventilation	Achieving the same air quality with window airing as with an hood with 95% capture efficiency	Dis-comfort >> E**	Low	Jacobs 2017b
CO2	Ventilation	Improvement air quality in sleeping room due to better use of ventilation grille Placement of self-regulating grilles Installation of mechanical supply or exhaust in sleeping room	Marginal Medium High	Low Middle High	

3.3 Effect of range hood in combination with filtering

In the Be Aware project (2019) based on a year during measurement campaign with optical particle sensors in 100 Dutch dwellings 50 percentile emissions patterns for $PM_{2.5}$ have been set up. Figure 1 shows a typical emission pattern for a Sunday in which $PM_{2.5}$ emissions can be seen due to preparation of breakfast, lunch and dinner. People are not all days present at home and certainly do not emit $PM_{2.5}$ due to cooking on all days. To accommodate these

differences 3 week emission patterns for the 50 percentile have been set up (to be published later). Based on these emissions patterns, simulations were carried out with the TRNSYS program to determine the effect of various interventions in different types of homes on the annual average $PM_{2.5}$ concentration and also the exposure in the living room / kitchen during presence. To this end, the TRNSYS building model is linked to the TRNFLOW/COMIS ventilation calculation model. The model consists of one room: living room / kitchen, with a volume of 100 m^3. The ventilation is according to building regulations. The outside air concentration in the Netherlands is typically 12 $\mu g/m^3$ on average, but can vary considerably over time. With west wind and / or rain the outside air concentration is often 1 $\mu g/m^3$, while with east wind the outside air concentration can rise to 20 or 40 $\mu g/m^3$ or even higher. In this study we used 1, 11,5 and 22 $\mu g/m^3$. For the cooking fumes, when the extractor hood is switched on with 83 dm^3/s drain, a capture efficiency of 95% is used (VentKook, 2018). For air cleaning, a stand-alone air cleaner with a Clean Air Delivery Rate of 200 m^3/hour has been selected that is continuously on.
Based on 4 airtightness levels, presence or absence of a cooker hood in the form of an extractor hood, whether or not air cleaning and 3 outside air concentrations, 4 x 2 x 2 x 3 = 48 simulations were performed for both ventilation system C (natural supply, mechanical exhaust) and D (balanced ventilation). For system D, additionally 48 simulations were performed to map the effect of filtering. In these simulations, an F7 filter in the air supply of the balanced ventilation (system D) was adopted, which removes 75% of the $PM_{2.5}$ from the ventilation supply air. For these simulations, it is assumed that the extractor hood is used during all cooking activities.

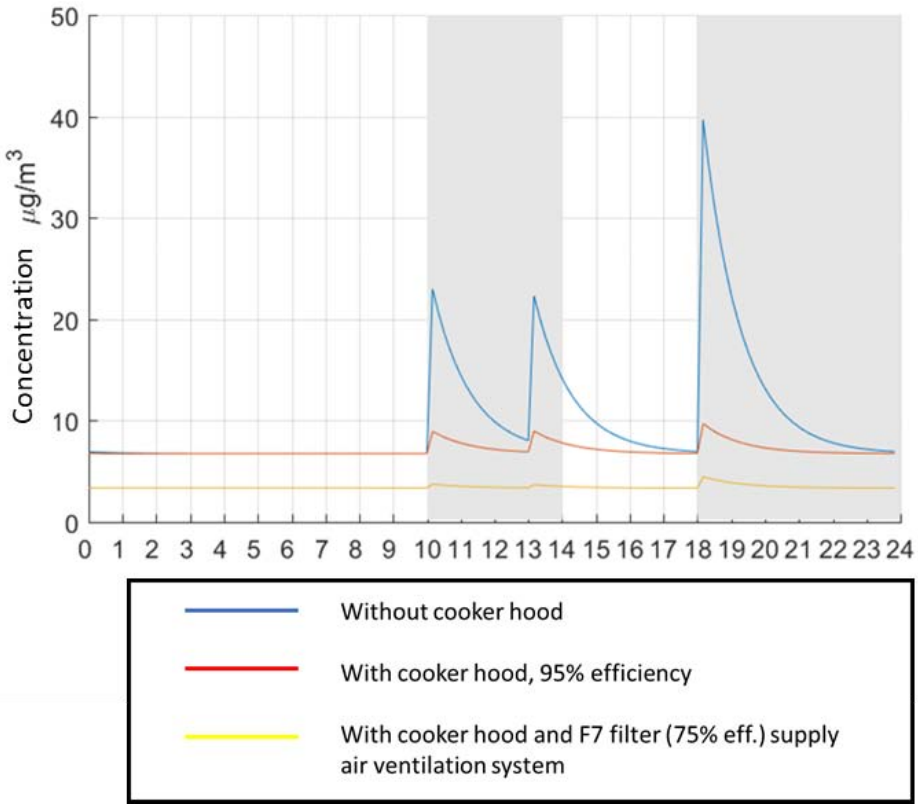

Figure: 1 Balanced ventilation system, $PM_{2.5}$ concentration progression over time, the grey blocks indicate the presence of persons (Sunday, week 2).

Figure 2 shows the simulated effects of the yearly averaged kitchen/living room $PM_{2.5}$ concentration as function of using a cooker hood and a F7 filter in the ventilation supply for four levels of airtightness. For the combined measures, with increasing airtightness the exposure of particulate matter increases. This is because in an leakier house fine dust infiltration is larger. In the most air tight house a cooker hood with 95% capture efficiency reduces the average exposure in the living room / kitchen with 51%. In combination with an F7 filter in the air supply the exposure is reduced with 82%.

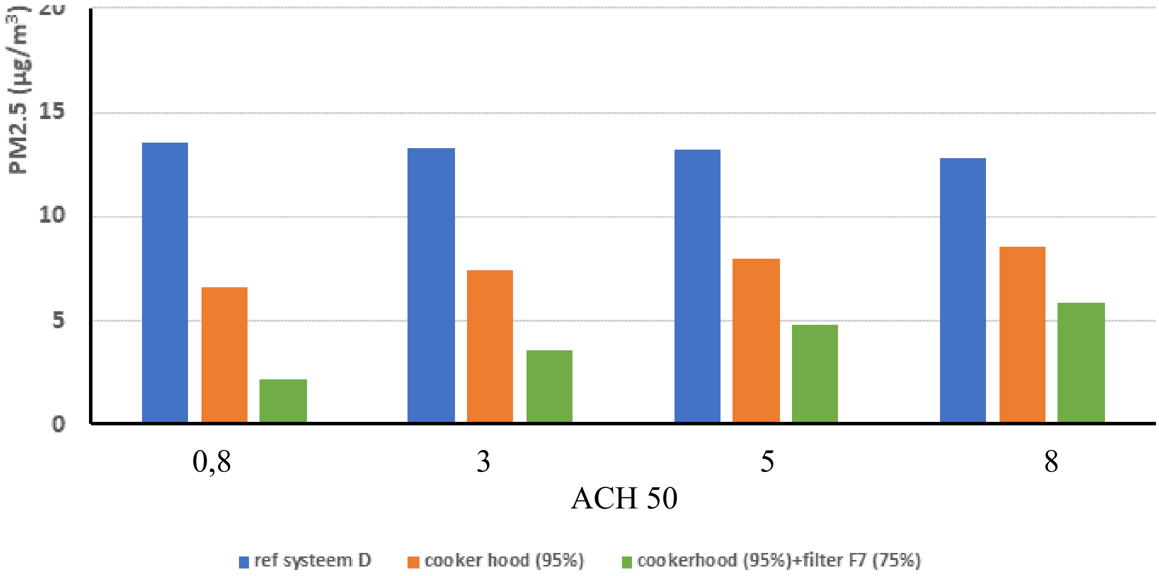

Figure 2; Average exposure to $PM_{2.5}$ in living room / kitchen with different measures

To estimate the health impact of these measures on the total exposure to $PM_{2.5}$ a typical scenario has been set up for the time period people remain in the kitchen/living room, sleeping room, at work or in the outside air, see table 2. For occupational exposure, a $PM_{2.5}$ concentration of 25% of the outdoor air concentration with a minimum of 1 µg/m^3 is assumed. This is a typical reduction in an office building where conventional air filters (F7) in the air treatment are applied.

Day of the week	**bedroom [hour]**	**livingroom [hour]**	**livingroom [hour]**	**work [hour]**
Table content				
Monday	9	5	2	8
Tuesday	9	5	2	8
Wednesday	9	5	2	8
Thursday	9	5	2	8
Friday	9	5	2	8
Saturday	9	10	5	0
Sunday	9	10	5	0

Table 3 lists for a number of measures the reduction in $PM_{2.5}$ exposure for a house with a typical air tightness (N50 = 3 ACH) for both ventilation system C (natural supply, mechanical exhaust) as D (balanced ventilation). It is interesting to see that e.g. for a house with ventilation system D the use of a cooker hood and the placement of a F7 filter the total weekly exposure is almost halved. This can be explained by the fact that the F7 filter not only cleans the air towards the kitchen/living room but also for the sleeping room in which relatively much time is spend.

Table 3 average yearly exposure at three ambient concentrations for different scenarios

Ambient air concentration [µg/m³]	**1**	**1**	**11,5**	**11,5**	**22**	**22**
Exposure according scenario	**[µg/m³]**	**reduction**	**[µg/m³]**	**reduction**	**[µg/m³]**	**reduction**
C, no cooker hood (reference)	3,0		7,4		11,8	
C, with cooker hood	0,7	76%	5,3	29%	9,8	17%
C, with air cleaner	0,9	70%	3,2	57%	4,7	60%
C, with cooker hood & air cleaner	0,4	86%	2,6	65%	4,7	60%
D, no cooker hood (reference)	2,5		8,2		13,8	
D, with cooker hood	0,8	67%	6,6	20%	12,3	11%
D, cooker hood + F7 filter	0,6	75%	4,3	48%	8,0	43%
D, with air cleaner	1,0	58%	3,8	54%	6,5	53%
D, with cooker hood & air cleaner	0,5	80%	3,3	60%	6,0	56%
D, as previous + F7 filter	0,4	83%	2,5	69%	4,6	67%

4 STRATEGIES TO IMPROVE INDOOR AIR QUALITY

In various countries, but also at European level, there are several regulations to reduce the energy consumption of homes. There are also various incentives and subsidies to save energy for existing buildings. In a very limited number of cases, the quality of the indoor air is taken into account. As noted earlier, an energy-efficient renovation, and even an energy-efficient new building, can also lead to a deterioration in indoor air quality. A positive example of how to combine energy savings with a good indoor climate is through a performance contract or even a renovation as a service. Within the Dutch non-profit "Stroomversnelling" the members offer a net zero energy renovation through a service contract. For a specific amount per month, the residents get a renovated house and a pre-determined amount of electricity, heat and hot water. There are also requirements for the indoor climate. Through a standardized data transfer protocol (API), data from the home is offered to the residents and housing corporation in a universal way. It is also possible to use this protocol to transfer indoor air quality data such as fine dust, CO_2 and humidity. This makes it possible for residents and housing corporations to easily determine whether the renovation meets the performance in the field of energy and indoor air. This can create value for the end user and can be an important driver to deliver real energy efficient, healthy and comfortable renovations.

5 CONCLUSIONS

"***Build Tight and Ventilate Right***" was the slogan during the last decades. But it is not as simple as that. The studies in the last decade show that the problem of IAQ can only be solved in case:

- Eliminate avoidable harmful emissions from pollutants;
- Local extraction for indoor sources and filtering for outdoor sources;
- Smart control of the well-designed ventilation systems.
- Stand-alone filtering for unavoidable sources.

A combination of above strategies within NZEB dwellings makes it possible to reduce the yearly $PM_{2.5}$ exposure, in and outdoor of the house, with almost 50%. A positive example of how to combine energy savings with a good indoor climate is through a performance contract or even a renovation as a service. The main air borne pollutant with regard to health for such a contract or service could be $PM_{2.5}$ and CO_2 could serve as an indicator for ventilation and odor control.

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7 REFERENCES

Be Aware, TKI Urban Energy, final report (to be published 2020)

Borsboom, Wouter, Willem de Gids, Jennifer Logue, Max Sherman, Pawel Wargocki, Technical Note AIVC 68, *Residential ventilation and health*, INIVE EEIG, 2016

Broderick, Aine, Miriam Byrne, Sean Armstrong, Jerome Sheahan, Ann Marie Coggins, *A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing*, Building and Environment, Volume 122, September 2017, Pages 126-133

Chan W.R., et al., *Quantifying fine particle emission events from time-resolved measurements: method description and application to 18 California low-income apartments*, Indoor Air, 28: 89–101, 2018.

Clark, J.D., Walker I.S., Rojas G., (2018). *Measured pollutant removal performance of range-integrated downdraft exhaust kitchen ventilation device*, Indoor Air conference.

Day D.B., Xiang J. Mo J. Clyde M.A., Weschler C.J., Li F., Gong J., Chung M., Zhang Y., Zhang J., *Combined use of an electrostatic precipitator and a high efficiency particulate air filter in building ventilation systems: effects on cardiorespiratory health indicators in healthy adults*, Indoor Air, 28: 360 – 372, 2018.

Fisk W.J., *Health benefits of particle filtration*, Indoor Air 23: 357 – 368, 2013.

Fisk W.J., Chan W.R., *Effectiveness and cost of reducing particle-related mortality with particle filtration*, Indoor Air, 2017.

Jacobs P., *Fijnstof bronnen in en om woningen*, TVVL magazine, 2017.

Jacobs P., Cornelissen E., *Efficiency of recirculation hoods with regard to PM2.5 and NO2*, Healthy Buildings 2017, Lublin, Polen, 2017.

Jacobs P., Kornaat W., Borsboom W., *Fijnstof bij het koken - Het effect van kookafzuiging op fijnstofconcentraties in woningen*, Bouwfysica, 1, 2017b

Jacobs P., Borsboom W., *Test method for measuring pollutant removal of induction cooktop with integrated downdraft*, ISES-ISIAQ conference, Kaunas, Lithouwen.

Lioy P.J., Wainman T., Junfeng J.Z., Goldsmith S., *Typical Household Vacuum Cleaners: The Collection Efficiency and Emissions Characteristics for Fine Particles*, Journal of the Air & Waste Management Association, 1999.

Logue JM, McKone TE, Sherman MH, Singer BC. Hazard assessment of chemical air contaminants measured in residences. Indoor Air. 2011;21(2):92–109

Logue, J., Klepeis, N., Lobscheid, A., & Singer, B., *Pollutant exposures from natural gas cooking burners; a simulation-based assessment for southern California*. Environment Health Perspectives, 122: 43-50, 2014.

O’leary C., Kluizenaar Y., Jacobs P., Borsboom W., Hall I., Jones BG., *Investigating measurements of fine particle (PM2.5) emissions from the cooking of meals and mitigating exposure using a cooker hood*, Indoor Air, februari 2019.

Shu H., Jonsson B.A., Larsson M., Nanberg E., Bornehag C.G., *PVC flooring at home and development of asthma among young children in Sweden, a 10-year follow-up*, Indoor Air, 24: 227 – 235, 2014.

Singer B.C., Delp W.W., Price P.N., Apte M.G., *Performance of installed cooking exhaust devices, Indoor Air*, 22: 224 – 234, 2012.

Singer B. C., Delp W. W., Black D. R. Walker I. S., *Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house*, Indoor Air, 27: 780 – 790, 2017.

VentKook, Jacobs P., TNO 2018 R11055 *Openbaar eindrapport TKI Urban Energy VentKook - Ventilatiesysteem met goede kookafzuiging*, 2018.

Waring M.S., Siegel J.A., Corsi R.L., *Ultrafine particle removal and generation by portable air cleaners, Atmospheric environment*, 2008.