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Methodology to assess the exposure to cooking emissions in combination with the efficiency of range hoods

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SUMMARY
The purpose of this paper is to begin discussion regarding development of a methodology to assess the performance of residential range hoods with regard to exposure of people in their homes, which makes use of the capture efficiency measured in a laboratory settings. Two measurement methods for determining the efficiency in laboratory setting are described and discussed as well as an approach for simulating the exposure of people in homes is discussed.

KEYWORDS
Capture efficiency, cooking exhaust, exposure of users, $PM_{2.5}$

1 INTRODUCTION

Cooking can be a major source of the total exposure to particulate matter (Kluizenaar et al. 2017). Cooking with gas also emits other contaminants of concern, including nitrogen oxides (NOx), carbon monoxide (CO), formaldehyde (CH_2O) and ultrafine particles. Range hoods can be used to reduce odours, moisture and contaminants resulting from cooking. The capture efficiency with regard to these contaminants is determined by the thermal plume and the aerodynamic properties of the range hood. An important finding is that the capture efficiency for the front burners is lower than for the back burners (Rim 2012) especially for range hoods which do not fully cover the front burners (Singer 2012, Lunden 2015).
The thermal plume depends on the power input, temperatures, the dimensions of the pots and pans, and disturbances by the room air flow pattern. The power and temperatures during cooking depend on the type of cooking: gas, electrical heat resistance, infra-red or inductive cooking. The cooking temperature can vary from 100°C for boiling water to 300°C for high temperature cooking oils.

Scope

There is a large difference in cooking technologies and the efficiency of fuel use around the world. The difference derives from the food people want to cook and what they use for fuel. These parameters have a mayor influence on the source strength of contaminants emitted by cooking. In many countries bio-mass is the primary source of heat for cooking. In industrialized countries electric stoves and gas stoves are common. In the transition towards an energy neutral built environment induction cooking can be seen as a technology to reduce energy and emissions from cooking.
This article focuses on a method for assessing the exposure of people to cooking emissions at home using induction cooking and typical Dutch meals. These meals consist of cooked and pan fried potatoes and vegetables, cooked pasta and pan fried meat. The intent is to develop an approach for a metric that relates contaminant removal efficiency measured in the laboratory situation to occupant exposure in homes.

Challenges

There is an European standard (IEC 2011) for odour extraction. It is intended for testing both recirculation hoods and air extracting hoods. However, this standard does not address capture efficiency of contaminants. Jacobs (2017) has shown that a recirculation hood with activated carbon filters captures only about 30% of particle fine dust, $PM_{2,5}$.

There is also a European Standard for range hoods “EN 13141 part 3 range hoods for residential use”, in which many properties (e.g., blower/fan performance) of range hoods are evaluated but it does not address efficiency of contaminant capture/removal. Kim, Walker and Delp (2018) have developed a tracer gas capture efficiency test method for residential kitchen ventilation which has been used in a new ASTM (an international standards organization) test method: ASTM E3087. It measures capture efficiency under specific conditions that permits accurate comparison of range hoods under laboratory conditions. The test is developed for electric stoves that have a burner power output between gas and induction. The method uses two tracer gas emitter elements which emit 1000 W each and enable a surface temperature of 200 □C. The power output is representative during the heating up phase for cooking on gas, but the power consumption in practice is often lower due to higher efficiency frying meat and vegetables with induction cooking. It is likely that in the future these power and temperature requirements in the ASTM Standard will be reduced because they are proving difficult to achieve in some testing conditions and because they are at the highest end of cooking temperatures and more typical temperatures may be more appropriate for testing.

Relating laboratory-measured capture efficiency to the exposure of people in homes is a step which is not yet quite clear. The dose people are exposed to cannot directly be deduced from the efficiency of the range hood. The approach developed here includes the effect of the occupant/cook on the capture efficiency due to their presence within the flow field of the range hood. This article is intended to start the discussion for a European standard to determine the exposure of people in homes due to cooking emissions.

2 METHODS

The paper describes different laboratory test methods to assess the efficiency of range hoods. Two methods are compared with measurements. One of these methods is used as an example to estimate the exposure due to cooking emissions.

Capture efficiency with tracer gas methods

A kitchen has been set up with dimensions of 3,65 x 2,66 x 2,68 m. The test-chamber layout (dimensions, placement of cooker hood, size of cabinets etc.) is comparable with the standard for kitchen test facilities prescribed in the European standard IEC 61591 (2011). An improvement in comparison to IEC 61591 is that in the test chamber the supply air is delivered via a diffusive ceiling (Jacobs, 2008) to enhance a more homogeneous air volume, while minimising disturbance of the airflow under the hood. The exhaust air flows were adjusted by a centrifugal fan placed outside the room. The exhaust flowrate was determined and controlled by measuring the pressure drop over a orifice plate according to the international standard ISO 5167-2 (2003). The supply air rate was then adjusted in such a way that the pressure difference measured with a digital pressure sensor (Hastrup Walcher, EMA 84) between the test chamber and the surroundings was less than 0,5 Pa. This limits uncontrolled air flows through the test chamber envelope. The supply air was delivered by an HVAC unit equipped with an F7 filter (manufacturer: AFPRO filters).

To simulate the thermal plume conditions during frying two stir-fry-pans were kept at about 200 ºC on an induction cooking plate (manufacturer: Pelgrim IDK 464). The power settings of the induction plate for the left (7) and right (6) pan were 392 W for the left pan and 504 W for the right pan. Both pans were put on front position of the cooktop because this is the preferred cooking position for meat and vegetables frying based on analysis of 174 meals, see Figure 1.

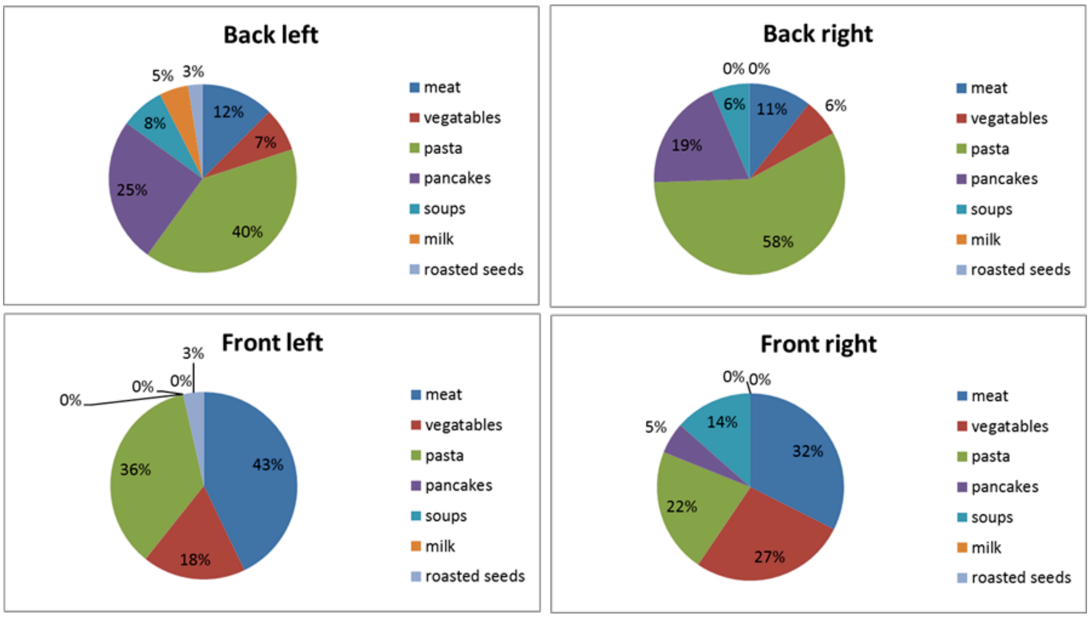

Figure 1. Preferred pan position during 1 week cooking in 9 Dutch dwellings (Jacobs 2016).

Cooking emissions was simulated by injecting CO_2 tracer gas in each pan with an 8 mm internal diameter copper tube with 15 holes of 1,5 mm diameter with discharge direction downward, see figure 2. The amount of tracer gas injection was adjusted to achieve between 1000 and 2000 ppm in the exhaust. The CO_2 flowrate was controlled with a mass flow controller (Bronkhorst). The particle concentrations were also measured during similar experiments in which full meals were cooked so that we could compare particle capture efficiency to gas capture efficiency. Additional testing used the ASTM (2017) method using two special emitters (courtesy of Lawrence Berkeley National Laboratory, LBNL) placed on electrical cooking plates, see figure 2. Due to equipment restrictions it was not possible to operate the heat plates at 1000 W. At 600 W the surface temperature was about 170 ºC, which is typical of frying temperatures.

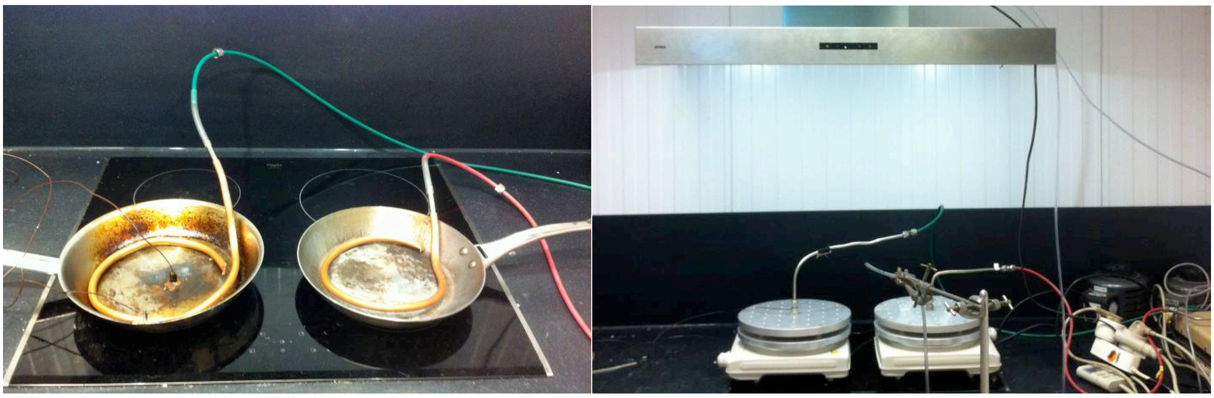

Figure 2. Left: Induction method with CO_2 injection in two stainless steel 24 cm stir-fry-pans in the front locations, the left pan is equipped with temperature sensors. Right: ASTM (2017) emitters on two electric heating (600 W) electric hot plates.

Occupant exposure assessment

The exposure of the user in a dwelling due to cooking emissions depends on many variables such as:

- Source strength and location on the cooktop
- Capture efficiency of the range hood
- Presence of the cook near the cooktop
- Ventilation and infiltration diluting contaminants and impacting capture efficiency
- Air transport of contaminants to other rooms
- Time spent in different rooms in the dwelling
- The effect of the outdoor pollution levels

The source strength is the emission rate of cooking related contaminants, e.g., 30 mg NOx, 12 mg formaldehyde, 50 mg $PM_{2,5}$ etc. Only contaminants not exhausted by the range hood enter the air in the dwelling and act as a source for the occupants. The dependence of capture efficiency on exhaust flow rate, range hood geometry, thermal properties of the sources, the number of burners in use, and the duration of the cooking event will all influence the exposure.

We might also consider the difference in particle size distribution and chemical composition for indoor and outdoor sources when determining occupant exposure, see figure 3.

The location and activity of the cook will also change exposure. In some cases people deliberately expose themselves to cooking contaminants, e.g., in order to smell what they are doing by placing their head under the range hood. The presence of a cook can change the airflow pattern around the cooktop, thus changing capture efficiency, or moving arms under range hoods when stirring or otherwise actively engaged in cooking. For example, it has been found that moving one arm under a range hoods four or five times with an average velocity of 0,1 m/s gives a flow rate exchange from the air under the range hood to the room of approximately 2 dm^3/s.

Ventilation and infiltration are responsible for the dilution of the emissions during cooking. The most simple approach to take these into account is assuming perfect mixing. But it will be quite clear that the person who is cooking will not be exposed to well mixed contaminants in the room. The air flow pattern in the room together with the momentum of the contaminants from under the range hood determines the real exposure. Some occupants will not be actively cooking, or even in the kitchen. To determine their exposure we need to account for contaminants moving between rooms. Any measurements of contaminants in indoor air will also include those transported into the dwelling by outside air. In this paper we will attempt to quantify and prioritize some of these effects.

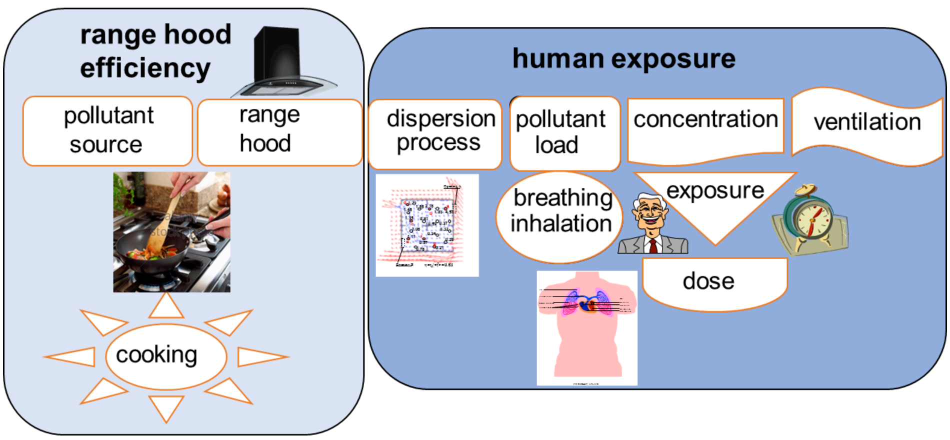

Figure 3. Range hood efficiency and human exposure (Borsboom et all. 2016)

An example of an exposure approach is given in the next paragraph

The residence time averaged $PM_{2,5}$ exposure for person in a typical Dutch dwelling has been calculated (Jacobs and Borsboom, 2017) using a 2-zone model. The following assumptions have been made:

- Cooking a full Dutch meal for 2,2 persons causes an emission of 35 mg $PM_{2,5}$. This source strength has been measured under laboratory conditions by TNO and the University of Nottingham as an average of four typical meals for western European cooking. This value coincides well with the value found by Chan (Chan, 2017).
- A study (Maggi, 2015) of 3344 Dutch people showed that on the average a meal is cooked 5 times a week. Based on this an average daily emission of 25 mg $PM_{2,5}$ is derived.
- An open kitchen is assumed, with a volume of 96 m^3 including the adjacent living room. Assuming a typical Western European kitchen exhaust ventilation system, the make-up air flows from the rest of the dwelling towards the kitchen/living room, so it is assumed that with a closed door transport of $PM_{2.5}$ towards the rest of the dwelling is neglectable.
- Cooking was simulated using a 10 minute emission period with a constant emission rate of 41,6 µg/s, starting at 18.00 h.
- After the cooking the reduction due to ventilation, infiltration and deposition is simulated with an equivalent dilution flow of 28 dm^3/s for the kitchen/living room. Of which 40% is caused by ventilation and 60% by infiltration and deposition.
- The exposure was calculated over the period 18.00 – 23.00 h, which is a typical duration for stay in the kitchen/living room.
- During the time that the occupants are in the bedrooms (9 hours per day) and in the kitchen/living room before the cooking, no additional exposure due to cooking was assumed. No exposure was assumed during the 58 hours per week when occupants are outside the dwelling, i.e., we are only calculating the additional cooking-related exposure.
- The additional exposure of $PM_{2,5}$ due to cooking was averaged over a 15,7 hour stay per day in the dwelling: 7 x 24 = 168 hours, 168 – 58 = 110 hours, 110/7 = 15,7 h/day

3 RESULTS

Measured capture efficiency with tracer gas methods

Figure 4 indicates that the measured capture efficiency between the ASTM method (at 600 W burner power) and the induction method coincide well at higher exhaust flowrates. At the lowest exhaust flowrate the induction method gives a higher capture efficiency. One key observation is that the capture efficiency measured with both tracer gas methods at 83 dm^3/s coincides well with the measured $PM_{2,5}$ reduction percentages during the cooking of two full meals on the front burners with and without range hood: 93,1 and 95,4%. This indicates that the tracer gas methods are good indicators of both gas and particle capture efficiency, and that the measured capture efficiency is representative for the cooking of real meals including disturbances by the cook. Figure 5 shows the multizone simulation results with regard to the increase in $PM_{2.5}$ concentration due to cooking. The capture efficiency of the hood has the largest effect. There is also a small second order effect visible due to dilution, with more dilution at higher exhaust flows.

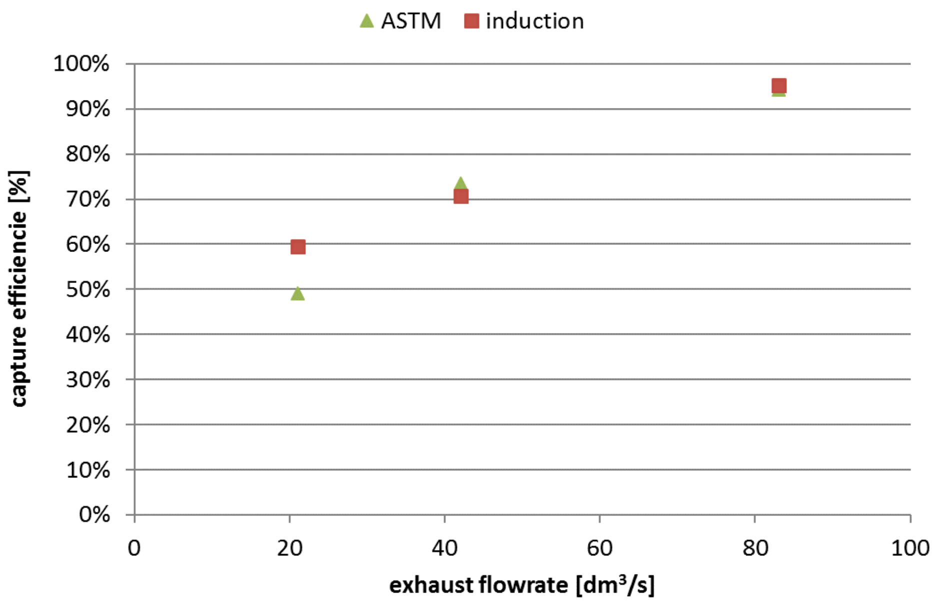

Figure 4. Relation between the capture efficiency and the exhaust flowrate for the ASTM and induction methods.

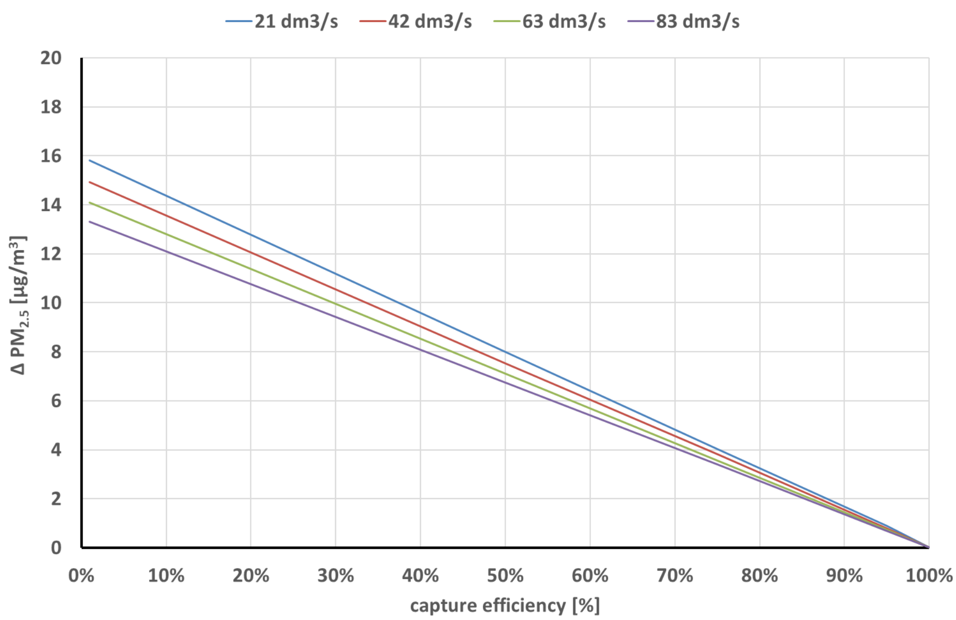

Figure 5. Residence time averaged $PM_{2.5}$ concentration increase in the dwelling as function of hood capture efficiency and exhaust flowrate during cooking.

4 DISCUSSION

The data in this study suggest that at high capture (95-80%) efficiency the capture efficiency of range hoods with regard to $PM_{2,5}$ can be measured by using CO_2 tracer gas in a way that is representative for real life conditions. This finding should be further supported by cooking full meals under several exhaust conditions and different types of hoods.

The exposure approach based on multi zone simulations has shown that the additional exposure toward $PM_{2.5}$ from cooking linearly decreases with higher capture efficiency. The results with regard two typical exhaust flowrates and three typical cooking exhaust configurations are graphicly displayed in figure 6.

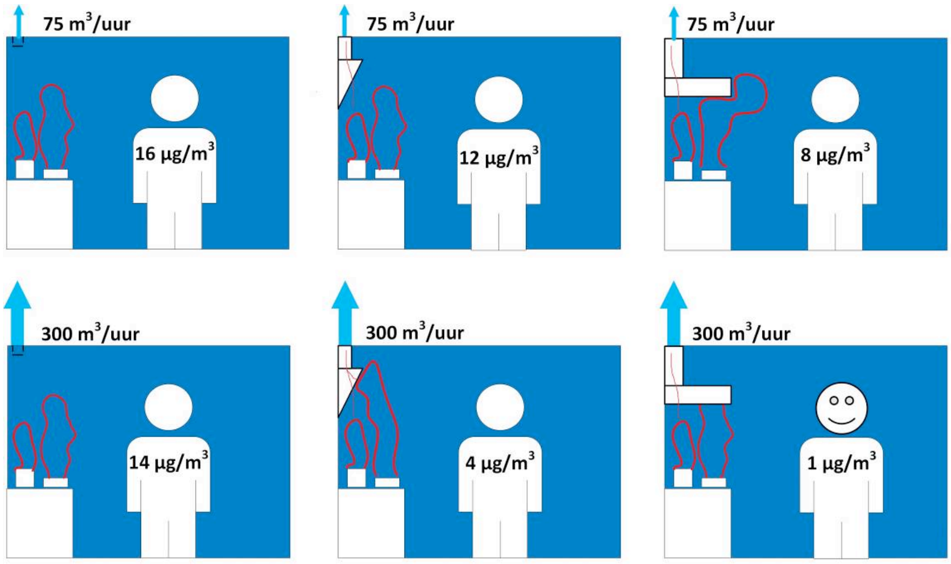

Figure 6. Annual average $PM_{2,5}$ concentration increase during occupied times in a dwelling due to cooking for different range hood flows and geometries

In the Netherlands the yearly averaged ambient $PM_{2,5}$ concentration is about 14 µg/m^3. Assuming an indoor/outdoor factor of 0,5 the indoor concentration due to ambient sources for a typical dwelling is estimated at 7 µg/m^3. Without a range hood the total exposure to $PM_{2,5}$ can be more than tripled to 16 + 7 = 23 µg/m^3. An effective range hood in combination with a sufficient high exhaust flow can reduce the increase below 1 µg/m^3. Therefore use of an appropriate range hood can keep concentrations below the WHO (2010) guideline value of 10 µg/m^3. The results are in line with the average findings of recent monitoring studies (Chan 2017, Jacobs 2016). However, on individual level large differences can be seen. In another recent study, Kim et al., 2018 measured 20 cooking events in 6 homes for $PM_{2.5}$ and 28 events in 9 homes for NO_2. The results showed roughly a doubling of $PM_{2.5}$ from 2.5 to 6 µg/m^3 and an increase from 6 to 22 ppb NO_2 during cooking activities with no range hood operation. There was considerable variability from event to event between zero more than factors of ten increase in these pollutant concentrations. Range hoods proved very effective at minimizing increases in these contaminants. A subset of four tests showed that range hood operation resulted in very small increases in contaminants when cooking: with less than 1 µg/m^3 (on average) changes in $PM_{2.5}$. Another set of seven tests showed increases of only 2 ppb NO_2 when range hoods were operated. Overall, all these field studies indicate that our simplified calculations provide reasonable estimates of cooking contaminant concentrations.

5 CONCLUSIONS

The different methods of determining the range-hood capture efficiencies have good general agreement and also agree with the results of $PM_{2.5}$ capture from real cooking events. Research is still needed to further develop methods for predicting cooking-related occupant exposure. This paper presents a first effort at quantifying methods to translate from efficiency to exposure. In the future we plan to develop a European standard using this occupant exposure approach.

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