Estimated distributions of $PM_{2.5}$ concentrations in the kitchens of the English housing stock for infiltration and mechanical ventilation scenarios

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ABSTRACT

Exposures to elevated concentrations of airborne fine particulate matter with diameter ≤ 2.5 µm ($PM_{2.5}$) have been linked to multiple negative health effects. Investigations into $PM_{2.5}$ exposures primarily focus on external concentrations, which are easier to monitor. However, there is a growing interest in indoor exposures, as people spend up to 70% of their time at home, concentrations in dwellings may have a greater influence on personal exposures. As widespread indoor monitoring is difficult, modelling can offer an alternative method to investigate concentrations in a stock of houses.

Cooking has been identified as a key source of $PM_{2.5}$ in non-smoking households. Existing models are sensitive to the emission rate used, yet typically represent cooking sources with a constant emission rate, despite emission rates having been shown to vary with food type and cooking method amongst other factors.

Ventilation rates are another determinant of concentrations. Whilst the English Building Regulations require purpose-provided, mechanical extract ventilation to be installed in kitchens of new dwellings, for existing dwellings, there is only a requirement to maintain existing installations. Furthermore, there is no guarantee that occupants use installed ventilation, therefore it may be useful to consider an infiltration-only scenario, as a worst-case.

This paper investigates steady state $PM_{2.5}$ concentrations in kitchens in the English housing stock using simple statistical modelling. A Monte-Carlo simulation is used to produce a distribution of steady-state concentrations under worst-case conditions, considering infiltration as the only form of ventilation. A probability density function (PDF) for $PM_{2.5}$ emission rates for toast is used, a source the authors have investigated. Kitchen input data was taken from the English Housing Survey, a statistically representative sample of the English housing stock.

For worst-case conditions, the steady-state concentration is predicted to exceed 25µg/m^3 (the WHO daily mean guideline) in all kitchens. Mechanical ventilation is predicted to reduce the steady-state concentrations for all scenarios considered. A *capture efficiency* > 60% for a cooker hood extracting at 30l/s has equivalent performance to a general extractor fan with an airflow rate of 60l/s. However, in the best case scenario considered, steady-state concentrations are predicted to exceed the WHO daily guideline in 30% of kitchens. This is for air extracted at 30l/s through a cooker hood with 80% capture efficiency.

KEYWORDS

cooking, range hood, model, Monte Carlo, policy

1 INTRODUCTION

Airborne solid or liquid particles with a diameter of less than 2.5µm are known as fine particulate matter ($PM_{2.5}$) (Pope and Dockery, 2006). When inhaled, these particles can bypass the body's defences due to their small size (Pope and Dockery, 2006), and exposure to elevated concentrations has been associated with an increased risk of chronic and acute respiratory and cardiovascular diseases (Lewtas, 2007). The UK Air Quality Standards Regulations (2010) set targets for reducing external concentrations of $PM_{2.5}$, and other pollutants, to comply with EU legislation. On average, people spend 70% of time in their own houses (Lader *et al.*, 2006). Total exposure can be considered as a function of the time spent, and concentrations found, in different microenvironments (Salthammer, 2011) and so indoor concentrations in dwellings may have a greater influence on personal exposures.

Indoor sources of $PM_{2.5}$ include smoking, cooking, combustion sources, such as burning incense, and aerosol sprays (Afshari *et al.*, 2005). The best mitigation method is to remove a source. However, cooking is a common household activity where source control is not possible. Pollutants can be diluted by the infiltration of ambient air and by purpose provided ventilation. Infiltration is a poor mechanism because its airflow rates are low and because it is generally desirable to illuminate it to save energy. Accordingly, purpose provided ventilation is the most appropriate mechanism. England's statutory Approved Document F (ADF) (HM Government, 2010) prescribes intermittent kitchen ventilation rates of 30l/s through a cooker hood or 60 l/s elsewhere, or a continuous rate of 13 l/s. In new dwellings these are a requirement, whereas it is only necessary to maintain existing ventilation systems in refurbishing dwellings. These ventilation rates have been chosen to remove moisture, and with the expectation that they will dilute NO_2 and CO emitted by gas cooking. $PM_{2.5}$ was not considered. Additionally, the lower airflow rate required by a cooker hood is based on an assumption that a significant proportion of emitted $PM_{2.5}$ are removed before they are allowed to mix in kitchen air, but there is no performance metric in ADF for cooker hoods. A *capture efficiency* may be defined as the percentage of emitted particles extracted either directly or during operation (Lunden *et al.*, 2015). Measured capture efficiencies have been found to vary between 12% (Lunden *et al.*, 2015) and 98% (Rim *et al.*, 2012) as a function of the airflow rate, installation height, hood capture volume, and the fraction of the cook top covered by the hood (Singer *et al.*, 2012 and Lunden *et al.*, 2015).

One measure to ensure indoor air quality (IAQ) is to use a metric, such as a pollutant threshold, an upper limit that should not be exceeded over a defined period of time. The WHO (2005) recommends that mean $PM_{2.5}$ concentrations for ambient air are less than $10\mu g/m^3$ per year and $25\mu g/m^3$ per day. These thresholds are also recommended indoors (WHO, 2010). Others stakeholders set different thresholds. The US National Air Quality Standards (EPA, 2015) require $35\mu g/m^3$ per year and $12\mu g/m^3$ per day and the WELL Buildings Standard (IWBI, 2016) sets a threshold of $15\mu g/m^3$. These values are set using toxicological and epidemiological knowledge of a pollutant's *effect threshold*, the concentration at which there is a radical change in occupant health. Then, ventilation rates (or other mitigation measures) can be prescribed to ensure that the effect threshold is only exceeded in a few percent of cases, say 5%. However, the smaller the percentile, the more onerous are the ventilation requirements. To do this, Salthammer (2011) proposes a statistical approach to generate a probability distribution function of concentration using Monte-Carlo simulation. By assuming that the pollutant is well mixed throughout once release, the steady-state concentration can be calculated using a simple mass-balance model whose inputs are the emission rate, the decay rate (a combination of ventilation and deposition for $PM_{2.5}$), and the room volume. If each input is considered to be a random variable with a known distribution, sampling from them and performing multiple calculations gives a distribution of steady-state concentrations.

This paper seeks to provide a rudimentary assessment of the English housing stock and the suitability of the English Building Regulations given in ADF for removing $PM_{2.5}$ emitted by cooking using Salthammer's method. Kitchen concentrations are predicted for different scenarios using a Monte-Carlo simulation informed by data from the English Housing Survey

(EHS) (DCLG, 2017). The predictions are used to consider the ventilation strategies, cooker hood capture efficiencies, and ventilation rates that might keep $PM_{2.5}$ concentrations below threshold limits in English kitchens in 95% of cases, and thus minimise occupant exposures to them.

2 METHODS

We follow the method outlined by Salthammer (2011) and use bespoke MATLAB code to run a Monte Carlo simulation to predict $PM_{2.5}$ concentrations in a representative sample of English kitchens emitted by a single cooking source. In a well-mixed space where the emission and ventilation rates are constant the steady state $PM_{2.5}$ concentration is an asymptote that is never reached. The rate at which the indoor concentration approaches steady state concentration is a function of the ventilation and emission rates. In a small space with a low ventilation rate and high emission rate, 95% of the steady-state concentration is reach in only a few minutes, but in larger well ventilated spaces it can take much longer. Accordingly, three distributions are predicted:

1. Kitchen steady state $PM_{2.5}$ concentrations, C_{ss} (µg/m^3);
2. The time taken to reach 95% of C_{ss}, T (minutes);
3. The time taken to reach the WHO (2005) 24 hour mean threshold of 25µg/m^3.

2.1 Model

We use a widely used mass balance model (see O'Leary & Jones (2017), Ott *et al.* (2006)) as the basis of our calculations.

$$C(t) \;=\; C_{ss} + (C(0) - C_{ss})e^{-(\lambda+k)t} \tag{1}$$

$$C_{ss} = C_b + \frac{(1-\eta)G}{(\lambda+k)V} \tag{2}$$

Here, the concentration at time t, $C(t)$ is a function of the steady state concentration, C_{ss}, initial concentration, $C(0)$, ventilation rate, λ, and deposition rate, k. C_{ss} is itself a function of the background concentration, C_b, source emission rate, *G*, capture efficiency, η, ventilation and the deposition rates defined in Equation 2. Equation 1 can be used to find the time, T, to reach a specific concentration, $C(T)$

$$\mathrm{T} = \frac{1}{(\lambda+k)}\ln\left(\frac{C(0)-C_{ss}}{C(\mathrm{T})-C_{ss}}\right) \tag{3}$$

2.2 Model Inputs

In this paper we assume that the only source of $PM_{2.5}$ is from cooking events, and that any $PM_{2.5}$ from previous events have been successfully removed. Therefore C_b and $C(0)$ are assumed equal to zero. All other inputs are modelled probabilistically, sampled from an appropriate distribution, and are assumed to be independent variables.

Emission rate, *G*

Reported $PM_{2.5}$ emission rates from cooking are highly varied, and have been shown to vary with fuel type, food type, cooking method and oil type (Torkmahalleh *et al.*, 2017). They are frequently based on a small number of measurements from which it is difficult to determine uncertainty. Therefore, a single cooking source of toasting bread is modelled, as the authors are particularly familiar with this source. Emission rates are uniformly sampled from an empirical cumulative density function (CDF) with μ = 0.22 mg/min and σ = 0.065 mg/min, derived from 26 repetitions of toasting bread (O'Leary & Jones, 2017) in an outdoor chamber. However, the emission rates have been recalculated using a calibration factor of 0.64 obtained from subsequent gravimetric sampling (see Jones *et al.* 2018).

Deposition rate, *k*

A deposition rate of 0.39 ± 0.16 h^{-1} from Ozkaynak *et al.* (1996) is used. This is based on 1780 personal monitoring measurements in non-smoking residences, and has been used previously in $PM_{2.5}$ modelling studies (see Hamilton *et al.* (2015), Das *et al.* (2014), Milner *et al.* (2014)). Deposition rates are assumed to be normally distributed, however, a deposition rate of 0 h^{-1} is assumed if the sampled value was negative.

Volume, *V*

The English housing stock comprises 22.3 million dwellings, of which a statistically representative sample of 16,150 dwellings is documented by the 2009 EHS (DCLG, 2017). Whilst not the most recent data, the 2009 dataset is selected to match the data set used to derive the infiltration rate distributions (see below). Entries with no recorded kitchen dimension data were ignored, with the remaining data set represents 99.75% of the housing stock. This data set was used to create an empirical CDF, from which volumes are sampled.

Ventilation rate, λ

Three ventilation conditions are considered: (i) infiltration only, a worst case scenario, (ii) local mechanical extract ventilation at 60 l/s, to meet ADF requirements, (iii) extract ventilation through a cooker hood at 30 l/s to meet ADF requirements.

Two distributions of infiltration rates found in English houses have been generated by Jones *et al.* (2015). The majority of English houses share a party wall with another house and because their permeability is unknown, they were either considered to be impermeable or as permeable as other walls. We have unified these distributions by sampling equally from both, thus assuming that half of all conjoined houses have permeable party walls and half have impermeable party walls.

For both mechanical ventilation scenarios, the ventilation rate is a function of the mechanical ventilation rate, Q_M, the infiltration rate, Q_N, and the building's air tightness. Jones and Lowe (2014) show that the total ventilation rate, $Q_T = Q_M$ in airtight houses, but in *leaky* houses $Q_T = Q_N + \frac{Q_M}{2}$. The ventilation rate can then be estimated in any house if

$$Q_T = \max\left\{Q_N + \frac{Q_M}{2}, Q_M\right\} \tag{4}$$

For both scenario (i) and (ii), it is assumed the emitted $PM_{2.5}$ mixes fully within the space and $\eta = 0$. In scenario (iii), to model the additional benefit of extracting at source via a cooker hood, the probabilistically selected emission rates are reduced by the capture efficiency, η, which has a value between 0 and 1 where 1 is 100% efficient. Section 1 shows that CEs vary considerably, and that there is no information in the literature about typical CEs for English devices. Accordingly, this value is deterministically applied and four different CEs are modelled: 20%, 40%, 60% and 80%.

2.3 Sampling Method

The sampling method follows that described by Das *et al.* (2014) and Jones *et al.* (2015). There are 4 direct input variables to find C_{ss}, which are assumed to be independent of each other. 100 sets of these variables are sampled at a time using a Latin Hypercube, and each set is applied to predict C_{ss} (see Section 2.1). The total sample size increases incrementally according to the number of sets. After each set of predictions is made, the overall mean (μ) and standard deviation (σ) for the entire sample is calculated. When the change in μ and σ from one set of samples to the next is ≤0.01%, the stopping criterion is met, and the total number of samples deemed adequate.

2.4 Sensitivity Analysis

A sensitivity analysis is used to test the dependence of steady state $PM_{2.5}$ concentrations on the model inputs. Here we follow the method of Jones *et al.* (2015) and a full description is found in the reference. The method tests for linear (Kendall's tau, Pearson's product moment, linear regression), monotonic (Spearman's rank correlation coefficient, rank-transformed standardized variables), and non-monotonic (Kolmogorov-Smirnov, Kruskal-Wallis) relationships between inputs and outputs. All inputs are ranked according to the magnitude of the regression coefficient. A fundamental requirement is that all tested inputs are independent of each other, which is also an assumption of the model.

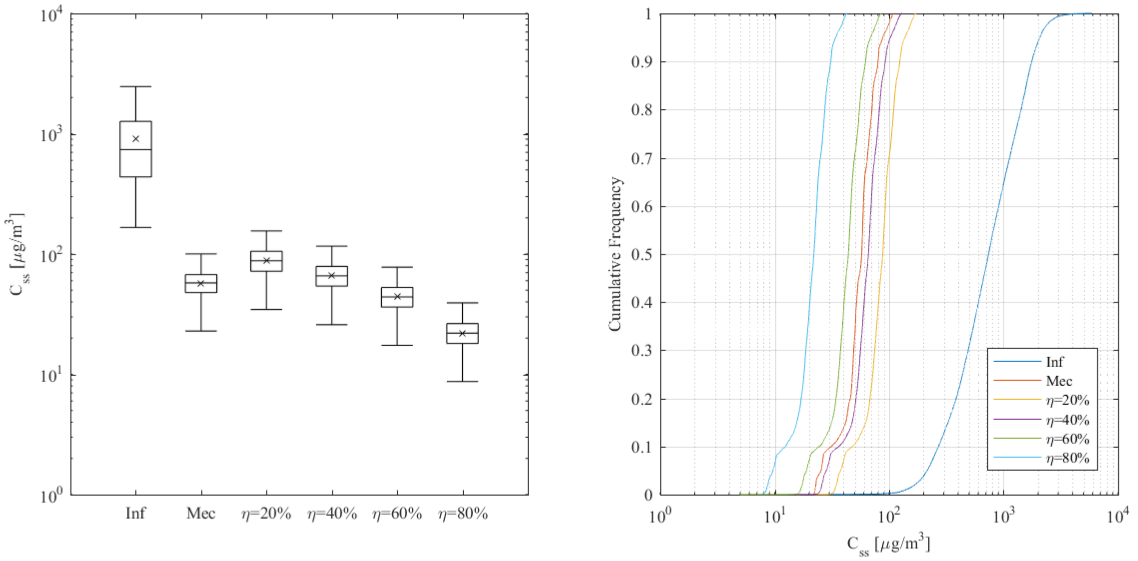
3 RESULTS

Figure 1 and Table 1 show the results for C_{ss} for the three scenarios. For the infiltration-only scenario, we predict that C_{ss} exceeds the WHO threshold in all kitchens. The concentrations are substantially reduced when a mechanical system is introduced, although a cooker hood with $Q_M = 30$ l/s and an efficiency of η >60% is required to give equivalent concentrations as a general kitchen extract fan with $Q_M = 60$ l/s. C_{ss} is predicted to exceed the WHO threshold in 95% kitchens if there is a general kitchen extract fan with $Q_M = 60$ l/s, and 30% kitchens for a cooker hood with $Q_M = 30$ l/s and $\eta = 88\%$.

Table 1: Steady State $PM_{2.5}$ Concentrations in English kitchens (μg/m^3) for all scenarios

	Infiltration only	**Q_M=60 l/s**	**η=20%***	**η=40%**	**η=60%**	**η=80%**
2nd percentile	166.4	22.9	34.6	25.8	17.4	8.7
25th percentile	437.8	47.8	72.0	54.1	36.3	18.1
50th percentile	737.8	57.5	87.9	65.9	44.0	22.0
75th percentile	1266.1	67.5	105.4	78.8	52.7	26.4
98th percentile	2468.1	100.2	155.6	116.3	77.7	39.2
Arithmetic mean	907.2	57.1	87.9	66.0	44.1	22.1
Standard deviation	616.4	17.6	27.9	20.8	13.9	6.9
Geometric mean	718.4	54.1	83.1	62.4	41.7	20.9

* η is capture efficiency

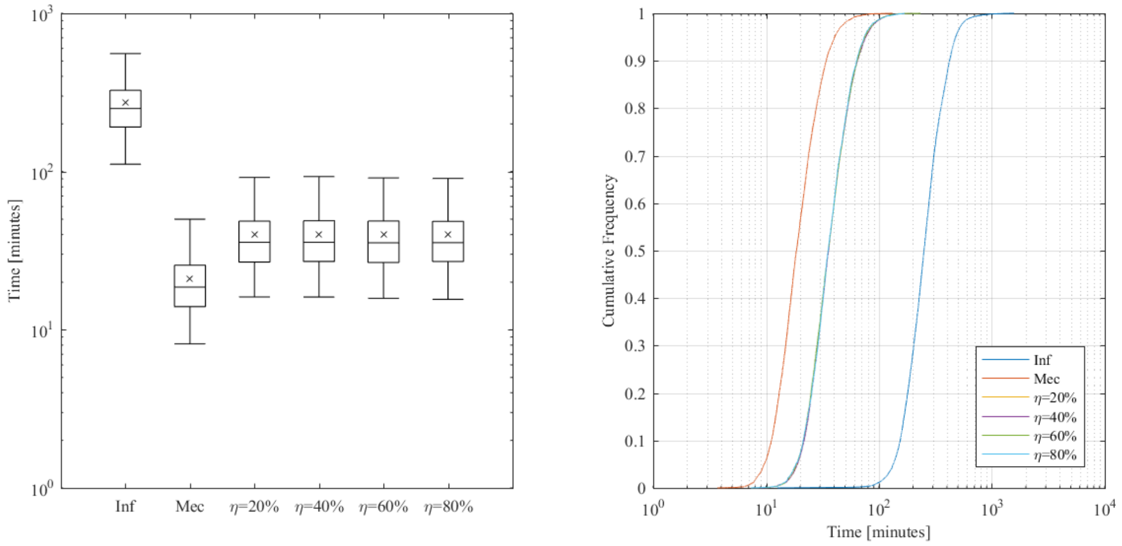


a) Whisker plot

b) Cumulative frequency

Figure 1: Steady-State Concentrations in English kitchens

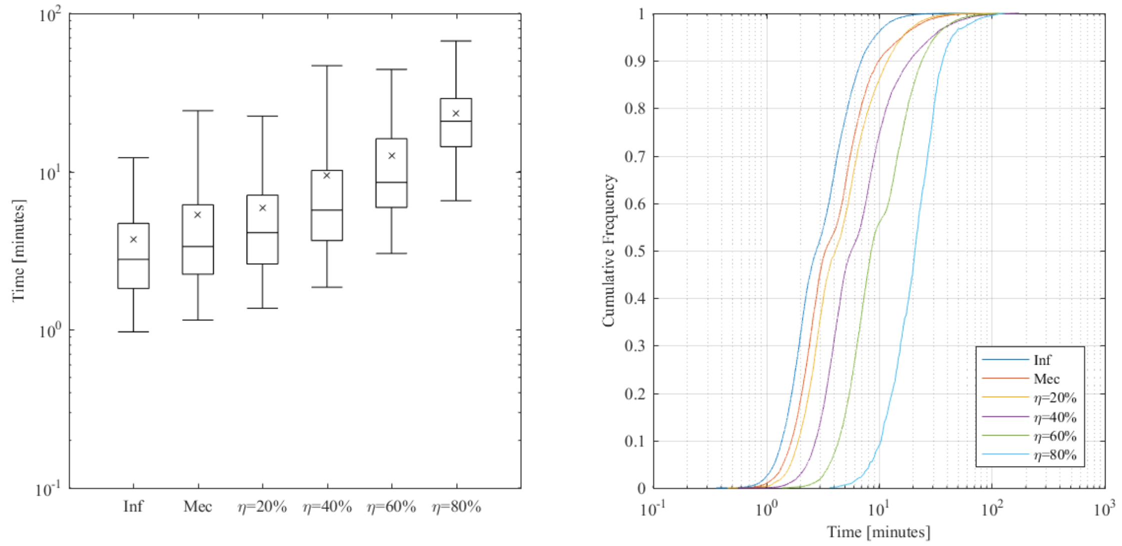
Figures 2 and 3 show the time required to reach 95% of steady state and the time to reach the WHO threshold of 25µg/m^3, respectively. Increasing the ventilation rate simultaneously reduces C_{ss} and the time required to reach 95% of C_{ss}, and increases the time required to reach 25µg/m^3. Equation 3 and Figure 2 show that η has no effect on the time taken to reach a fraction of C_{ss} because it cancels in the quotient. However, Equation 3 and Figure 3 show that increasing η also increases time taken to reach a specific concentration because it reduces the fraction of all emitted particles allowed to mix in a kitchen space.



a) Whisker plot

b) Cumulative frequency

Figure 2: Time (minutes) to reach 95% of C_{ss}



a) Whisker plot

b) Cumulative frequency

Figure 3: Time (minutes) to reach 25 µg/m^3

3.1 Sensitivity Analysis

The sensitivity analysis described in Section 2.4 is used to determine the relative importance of the input variables on the C_{ss} predictions. All inputs are obtained simultaneously by the Latin Hypercube sampling method and so any interactions between them are accounted for. The ranks of each model input are given in Table 2, where 1 indicates the most important because it is the analysis with the highest observed correlation or regression coefficient. Emission rate is ranked the most influential by all tests, with the deposition rate the least important. This further emphasises the need to investigate $PM_{2.5}$ emission rates from cooking. All relationships between these inputs and outputs were statistically significant, where $p \ll 0.05$.

Table 2: Sensitivity of C_{ss} to model inputs. 1 is the highest rank.

Input	Kendall τ rank	Pearson rank	Spearman Rank	Linear regression rank	Kolmogorov-Smirnov rank
Emission Rate	1	1	1	1	1
Infiltration Rate	3	3	3	3	3
Deposition Rate	4	4	4	4	4
Kitchen Volume	2	2	2	2	2

4 DISCUSSION

The predictions given in Section 3 indicate inconsistencies in our knowledge of cooking emission rate, cooking events, and in the ADF ventilation requirements for extractor fans (airflow rate of 60l/s) and cooker hoods (airflow rate of 30l/s) in English kitchens. ADF does not specify a minimum cooker hood capture efficiency that will give equivalent performance to the extractor fan due to its close proximity to the emission source. However, equivalent performance is only predicted for capture efficiencies of 60% and above. Rim *et al*. (2012) measured ultrafine particle capture efficiencies ranging from around 30% to over 90%. However, the higher capture efficiencies were measured at flow rates over 180l/s, which are much higher than the 30 l/s required by ADF. Lunden *et al*. (2015) measured a similar range of CEs, but the lowest flow rate measured was 51 l/s. Without investigation, it is impossible to know whether existing hoods in English dwellings meet ADF requirements, or what CEs are achieved.

Figure 1 shows that a mechanical system reduces steady state concentrations. For the predicted improvements to be achieved, all dwellings require a mechanical extract ventilation system in the kitchen to be installed. According to the 2009 EHS data, only 47% of kitchens are fitted with any form of extractor fan (DCLG, 2017). These could include venting and recirculating cooker hoods, and local continuous or intermittent extractor fans, as the survey does not specify. Therefore, it would be helpful if the next EHS recorded the fan type. There is no means to ensure the remaining 53% kitchens are fitted with an appropriate system, as ADF only requires the maintenance of existing systems. This should be considered in the next revision of ADF.

Logue *et al*. (2014) used simulation to investigate the effects of installing cooker hoods in Southern Californian houses, and found that their implementation with capture efficiency 55% reduced the percentage of homes exceeding standards for NO_2, CO and HCHO. Although $PM_{2.5}$ was not modelled, their conclusions suggest that a cooker hood would also reduce $PM_{2.5}$ concentrations.

In the best case scenario considered, where air is extracted through a cooker hood at 30 l/s with a capture efficiency of 80%, C_{ss} exceeds the WHO threshold in 30% of kitchens. However, a limitation of this investigation is the use of steady state concentrations, as these are unlikely to be reached, due to the relatively short cooking emission durations. Adams and White (2015) suggest a minimum cooking period of 30 minutes to cook a main meal. With no purpose provided ventilation, a 30 minute source emission would not cause concentrations to approach steady state in any houses, although concentrations would exceed 25 μg/m^3 in almost all kitchens; see Figure 3b. With a 60 l/s or 30 l/s extract ventilation rate, concentrations would near steady state in 84% or 34% houses, respectively; see Figure 2b.

The length of the cooking event is an unknown and is not an input to the model, but it is clearly an important parameter that is needed to put the predictions into perspective. For example, 78% kitchens exceed the WHO threshold if the cooking event is 5 minutes long and there is no purpose provided ventilation (infiltration only scenario). This reduces to 64% of kitchens when a 60 l/s extractor fan is used. However, only 0.6% of kitchens exceed the WHO threshold if a cooker hood is used that extracts air at 30 l/s and has $\eta = 80\%$. A 5 minute event is approximately the time it takes to make a quick snack, such as toast or an omelette.

We used a source emission rate for toast of 0.22 ± 0.065 mg/min. This is relatively low when compared to other cooking emission rates found in literature. Dacunto *et al.* (2013) found emission rates ranging from 0.1 mg/min for frozen pizza to 15.2 mg/min for fried chicken breast. As the steady state concentration is most sensitive to emission rates, the predicted C_{ss} is not representative of all cooking sources. An improved model could be developed by including emission rates from a wider range of sources. This would require an understanding of the types of food cooked and methods used, and their corresponding emission rates.

Our model assumes that kitchen volume and infiltration rate can be considered independent variables, which may not be true. This could be improved by modifying the infiltration rate by dwelling type. Here, the EHS gives the dwelling type which could be paired with a distribution of infiltration rates specific to the dwelling type, such as those generated by Jones *et al.* (2015).

This simulation only considered the intermittent ventilation requirements from ADF. There is an alternative requirement of 13 l/s continuous extract ventilation; however, a more complex, time-resolved model would be necessary to compare the intermittent and continuous ventilation requirements.

There is work to do before suitable ventilation rates and capture efficiencies can be chosen for English kitchens that minimize occupant exposure to $PM_{2.5}$ emitted by the cooking of food. Work is also required to estimate the increase in housing stock energy demand required to power mechanical ventilation devices and the associate increase in carbon emissions. However, this work highlights key issues that must be overcome in the short and medium terms, and shows that provisional ventilation rates should be available in the near future.

5 CONCLUSIONS

This paper uses a Monte Carlo simulation to predict steady-state $PM_{2.5}$ concentrations in English kitchens. For a worst case scenario, where infiltration is the only form of ventilation, C_{ss} is predicted to exceed the WHO 24-hour guideline in all kitchens. The predicted C_{ss} decreases for all the mechanical ventilation conditions considered. Approved Document F requires either 60l/s general kitchen extract ventilation, or 30l/s if through a cooker hood. Predicted C_{ss} distributions suggest a cooker hood capture efficiency of at least 60% is required to match the conditions from extracting at 60l/s elsewhere. Additionally, C_{ss} exceeds the WHO threshold in 95% houses when mixed air is extracted at 60l/s. When a cooker hood with flow rate 30l/s and 80% capture efficiency is modelled, we predict C_{ss} will exceed the WHO threshold in 30% kitchens.

Increasing the ventilation rate simultaneously reduces the steady-state concentrations and time to reach 95% of steady-state, and increases the time to reach the WHO daily mean guideline. Increasing the capture efficiency does not affect the time taken to reach a fraction of the steady-state concentration, however, it does increase the time taken to reach a specific concentration because it reduces the fraction of emitted particles allowed to mix in the kitchen air.

Toasting bread was the only modelled cooking source, due to limitations in available emissions rate data. However, emission rates from this source are lower than many of those reported from other cooking sources. This will be broadened to include other cooking methods and foods in the near future, especially as the sensitivity analysis shows that the steady state concentration is most sensitive to the emission rates.

Overall, the results suggest the kitchen ventilation requirements need revising to include cooker hood capture efficiencies. However, the energy penalty of changes has not yet been assessed, and so should be considered in future work.

6 REFERENCES

Adams, J. and M. White (2015). *Prevalence and socio-demographic correlates of time spent cooking by adults in the 2005 UK Time Use Survey. Cross-sectional analysis.* Appetite 92: 185-191.

Afshari, A., U. Matson and L. E. Ekberg (2005). *Characterization of indoor sources of fine and ultrafine particles: a study conducted in a full-scale chamber*. Indoor Air 15(2): 141-150.

Air Quality Standards Regulations (2010) Available at: http://www.legislation.gov.uk/uksi/2010/1001/contents/made

Dacunto, P. J., K.-C. Cheng, V. Acevedo-Bolton, R.-T. Jiang, N. E. Klepeis, J. L. Repace, W. R. Ott and L. M. Hildemann (2013). *Real-time particle monitor calibration factors and PM2.5 emission factors for multiple indoor sources*. Environmental Science: Processes & Impacts 15(8): 1511-1519.

Das, P., C. Shrubsole, B. Jones, I. Hamilton, Z. Chalabi, M. Davies, A. Mavrogianni and J. Taylor (2014). *Using probabilistic sampling-based sensitivity analyses for indoor air quality modelling.* Building and Environment 78: 171-182.

DCLG. (2017). *English Housing Survey, 2009: Housing Stock Data*. [data collection]. 3rd Edition. UK Data Service. SN: 6804, http://doi.org/10.5255/UKDA-SN-6804-3

EPA. (2015). *NAAQS Table*. Retrieved 25 Jun, 2018, from https://www.epa.gov/criteria-air-pollutants/naaqs-table.

H.M. Government (2010). *The Building Regulations 2000. Approved Document F,* Ventilation. Norwich, Norwich : TSO.

Hamilton, I., J. Milner, Z. Chalabi, P. Das, B. Jones, C. Shrubsole, M. Davies and P. Wilkinson (2015). *Health effects of home energy efficiency interventions in England: a modelling study*. BMJ Open 5(4).

IWBI. 2016. *The WELL Building Standard, Version 1.0*. International WELL Building Institute (IWBI). Delos Living LLC, New York, USA.

Jones BM, Lowe RJ. 2014. *Predicting the Optimum Air Permeability of a Stock of Detached English Dwellings*. 35th AIVC Conference. Poznan, Poland. 2014. p. 575-86.

Jones, B., P. Das, Z. Chalabi, M. Davies, I. Hamilton, R. Lowe, A. Mavrogianni, D. Robinson and J. Taylor (2015). *Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies*. Building and Environment 92: 644-656.

Jones BM, G Phillips, C O'Leary, C Molina, I Hall, M Sherman. 2018. *Barriers to using $PM_{2.5}$ concentrations as an input to metrics of indoor air quality*. 39th AIVC Conference. Antibes Juan-Les-Pins, France. 2018.

Lader, D., S. Short and J. Gershuny (2006). *The time use survey, 2005: how we spend our time*. London, UK, Office for National Statistics.

Lewtas, J. (2007). *Air pollution combustion emissions: Characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects*. Mutation Research/Reviews in Mutation Research 636(1–3): 95-133.

Logue, J. M., N. E. Klepeis, A. B. Lobscheid and B. C. Singer (2014). *Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California*. Environmental Health Perspectives 122(1): 43-50.

Lunden, M. M., W. W. Delp and B. C. Singer (2015). *Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods*. Indoor Air 25: 45–58.

Milner, J., C. Shrubsole, P. Das, B. Jones, I. Ridley, Z. Chalabi, I. Hamilton, B. Armstrong, M. Davies and P. Wilkinson (2014). *Home energy efficiency and radon related risk of lung cancer: modelling study*. BMJ 348.

O'Leary C, Jones BM. 2017. *A Method to Measure Emission Rates of PM2.5s from Cooking*. AIVC Conference 2017. Nottingham, UK.

Ott, W. R. (1990). *A Physical Explanation of the Lognormality of Pollutant Concentrations*. Journal of the Air & Waste Management Association 40(10): 1378-1383.

Ott, W. R., A. C. Steinemann and L. A. Wallace (2006). *Exposure Analysis: Mathematical Modeling of Indoor Air Quality*, CRC Press: 533.

Ozkaynak, H., J. Xue, J. Spengler, L. Wallace, E. Pellizzari and P. Jenkins (1996). *Personal exposure to airborne particles and metals: results from the Particle TEAM study in Riverside, California.* Journal of exposure analysis and environmental epidemiology 6(1): 57-78.

Pope, C. A. and D. W. Dockery (2006). *Health Effects of Fine Particulate Air Pollution: Lines that Connect*. Journal of the Air & Waste Management Association 56(6): 709-742.

Rim, D., L. Wallace, S. Nabinger and A. Persily (2012). *Reduction of exposure to ultrafine particles by kitchen exhaust hoods: The effects of exhaust flow rates, particle size, and burner position.* Science of The Total Environment 432: 350-356.

Salthammer, T. (2011). *Critical evaluation of approaches in setting indoor air quality guidelines and reference values*. Chemosphere 82(11): 1507-1517.

Singer, B. C., W. W. Delp, P. N. Price and M. G. Apte (2012). *Performance of installed cooking exhaust devices.* Indoor Air 22(3): 224-234.

Torkmahalleh, M. A, S. Gorjinezhad, H. S. Unluevcek and P. K. Hopke (2017). *Review of factors impacting emission/concentration of cooking generated particulate matter*. Science of The Total Environment 586(Supplement C): 1046-1056.

WHO (2005). *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide*, Word Health Organization.

WHO (2010). *WHO guidelines for indoor air quality: selected pollutants*, Word Health Organization.