PHOENICS Case Study: CFD investigation for reducing personal exposure to particulates emitted from residential Chinese cooking.

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Introduction

Cooking is known to be a major source of indoor particulate matter (PM), particularly in Chinese households (Abdullahi et al., 2013; Zhao and Zhao, 2018). When compared with Western residential cooking, the indoor air pollution generated by Chinese cooking is much more severe owing to the special cooking style; and, for this reason, it has become an important influential factor on indoor air quality in Chinese residences. Chen et al (2018) found that the high temperatures of over 170 °C required for some traditional Chinese cooking methods, such as stir-frying, pan-frying, and deep-frying, generate high levels of fine particulate matter under 2.5 µm (PM2.5).

Studies have associated the development of lung cancer among Chinese women, including non-smoking women, with their exposure to cooking oil fumes (COF) (Hung et al., 2007; Wang et al., 2014). Some measured data show that even with the cooker range-hood operating, the PM2.5 concentration in the kitchen could still reach over 500 µg/m^3 with bad ventilation (Chen et al., 2018).

The overall objective of this research was to explore possible control measures of air pollution during cooking by using PHOENICS-FLAIR to simulate the PM2.5 levels in a typical residential arrangement, as shown in the kitchen and adjacent living room depicted in Figure 1.

Model Description

The kitchen contains cooker, a cooking pan, a range hood, an open window, and an open doorway to the living room. Other neighbouring rooms, including the bathroom, were not included explicitly in the CFD model, but rather were represented in terms of open doorways with constant low-level inflow and high-level outflow boundaries, whose volume flow rates and incoming time-varying PM2.5 concentrations in µg/m^3 were determined by the multi-zone computer program CONTAMW3 (Dols & Polidoro, 2015). The multi-zone model uses the well-mixed assumption for each room to calculate airflow, energy and species transport between the rooms of a building, and between the building and outdoors. Further information on its use in the present study has been given by Zhao and Zhao (2019).

The range hood was defined by a constant volume extraction rate of 530 m^3/hr, and the cooking pan was modelled as a heat source of 2.5kW with a PM2.5 emission rate of 5 mg/min. The external ambient temperature was taken as 25°C, and the open window of the kitchen was defined as a pressure boundary at atmospheric pressure.

The kitchen measures 1.6m by 3.5m by 2.8m, and the adjoining living room 3m by 4.5m by 2.8m. A breathing space with the dimensions 0.25m x 0.5m x 0.5m, the centre of which was 1.5m and 1.2m above the floor in the kitchen and the living room respectively, was used by Zhao and Zhao (2019) to determine the average PM2.5 concentration in each room between different cases.

Gravitational effects were represented by means of the reduced-pressure formulation, where buoyancy forces appear in the momentum equation in terms of a perturbation density from ambient. Turbulence was represented by means of the standard k-ε model with empirical wall functions.

The Ideal Gas law was used to obtain the variation of air density with temperature, and the drift-flux model was applied to represent particle transport and its slippage relative to the air due to gravitational effects (Zhao *et al.*, 2009; Zhou and Zhao, 2011).

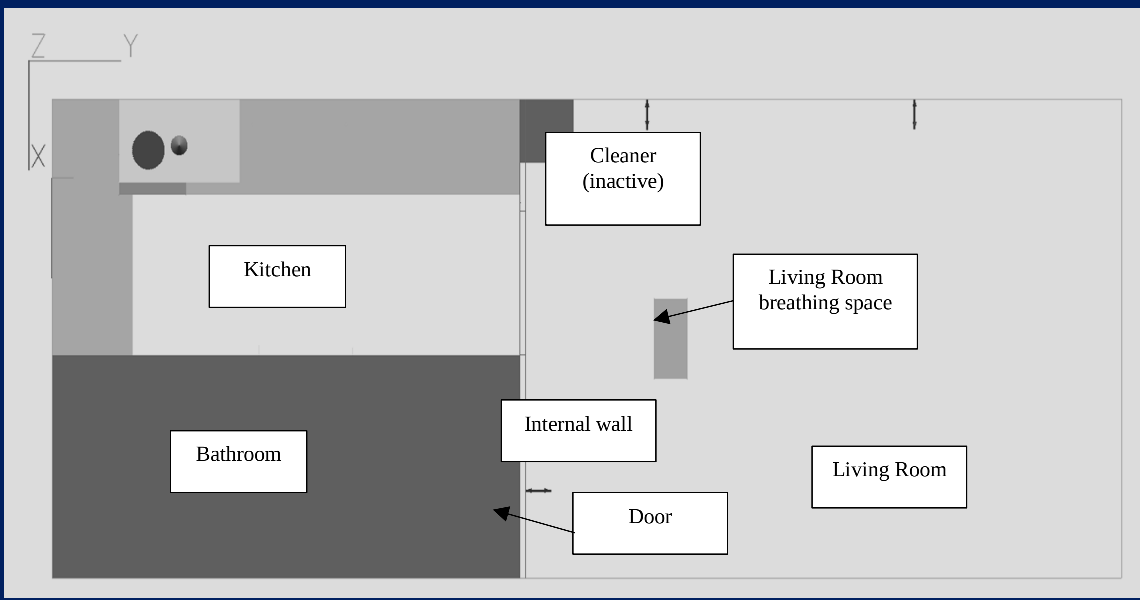
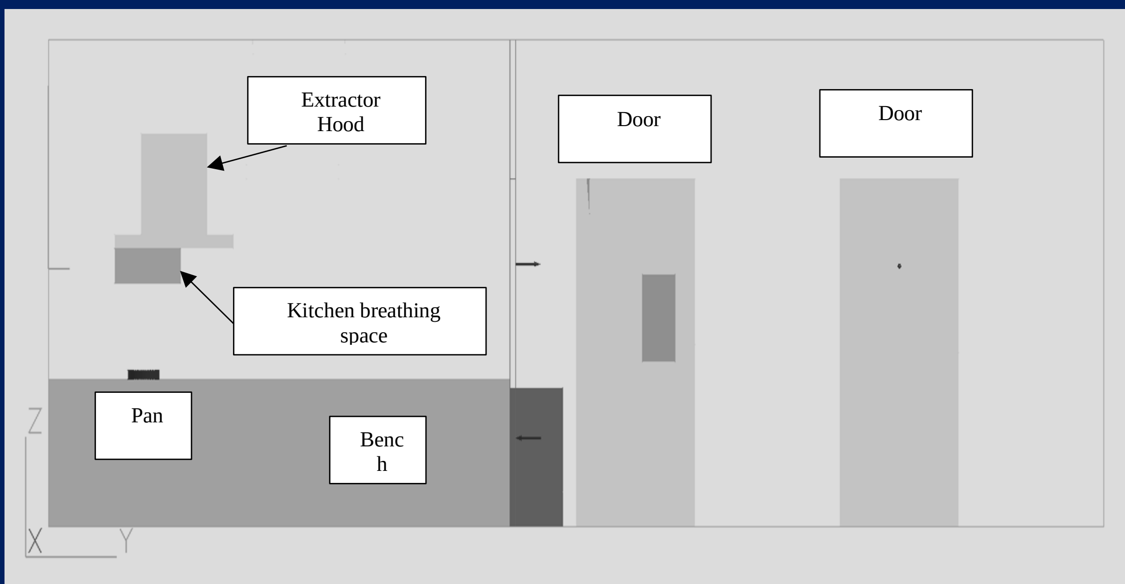


Figure 1: Plan (top) and front (bottom) elevation of the model layout showing position and size of all major structures



Results and Discussion

Zhao and Zhao (2019) first considered first a base case, and then a further eight cases to study the effect of two types of control measure for improving air quality, namely: (a) configuring a ceiling screen in the kitchen to obstruct COF pervasion; and (b) employing an air cleaner in the living room and/or kitchen to remove PM2.5. The different cases varied the positioning of the ceiling screen and air cleaners. Steady-state solutions were performed to produce the flow and thermal solution fields in the absence of particles. Then, for each case, a transient restart simulation was performed from the steady solution to predict the temporal evolution of the particle concentration field. The transient simulation covered 10 minutes duration using a time step of 1s. Figures 2 and 3 show some typical CFD results for the base case in terms of temperature contours and PM2.5 iso-surface contours, respectively. In Figure 2, temperatures beyond the contour limit of 30°C are displayed as the limit colour; and the figure also includes velocity vectors that are capped at 0.5 m/s for clarity, although this is exceeded only just below the extractor hood.

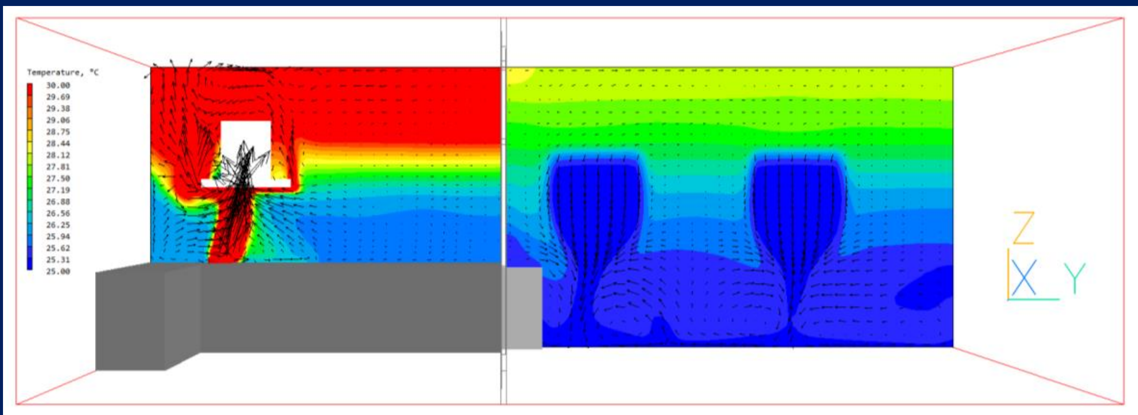


Figure 2: Temperature contours and velocity vectors across the kitchen and living room in the X-plane in line with the extraction hood.

The iso-surface in Figure 3 corresponds to a PM2.5 value of 60 µg/m^3. This figure serves to illustrate the progression of cooking-oil particulates from the kitchen and into the living-room space.

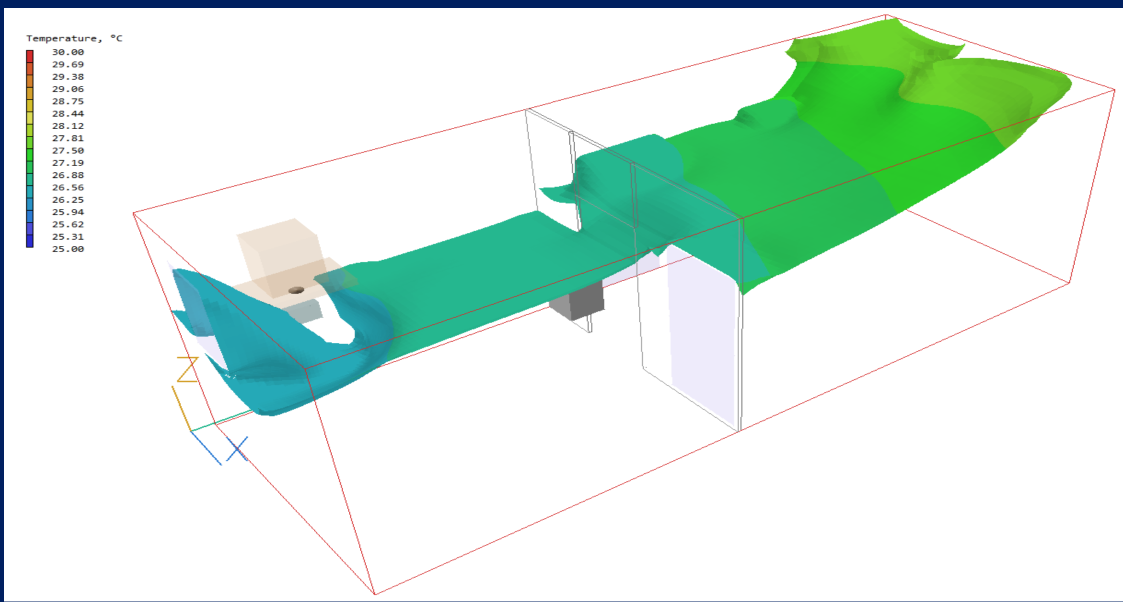


Figure 3: Iso-surface plot of PM2.5 concentration (60 µg/m^3) coloured by temperature.

The results of this and all other cases were highlighted and discussed in detail in the paper of Zhao and Zhao (2019), including reports on the effects of the different control measures. For example, the use of ceiling screens in the kitchen was found to reduce the PM2.5 concentration in the living room by up to 10%, depending on the number of screens and their location. Not surprisingly, the use of an air cleaner improved the air quality in the living room significantly, and some further improvement was obtained when using both control measures.

Conclusion

This type of research has shown how PHOENICS-FLAIR can be used to provide insight into the flow, temperature and concentration fields generated by residential cooking. These results can then be used to provide some guidance in engineering-control strategies of air pollution. Further reading can be found in the experimental paper of Zhao and Zhao (2020); and in the references cited, including the original CFD study of Zhao and Zhao (2019).

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