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The CFD analysis of the effects of the size and location of an Air-Inlet in domestic kitchen extraction

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ABSTRACT

An investigation has been carried out to understand the optimal size and location for air-inlets within confined spaces such as domestic kitchens for improved ventilation processes. This analysis was carried out using Computational Fluid Dynamics (CFD) techniques and Indoor Air Quality (IAQ) factors and comfort levels were used as performance indicators.

A model kitchen was constructed including a gas range cooker and an Extraction Hood and the cooking process was simulated. Carbon Dioxide (CO_2) concentration was used as the IAQ indicator to establish efficiency of the ventilation process. The effects of the various air-inlet sizes and locations were determined by observing the performance of the kitchen hood in maintaining the recommended level of CO_2 within the room.

Keywords air-inlet, optimal size, optimal location, domestic kitchen extraction, CFD, IAQ, Range cooker, extraction hood, cooking, contaminants, HVAC

1 INTRODUCTION

Contaminants in our indoor environment can increase the risk of illness. Several studies have consistently mentioned the indoor air contaminants as an important environmental health problem [1]. In domestic kitchens, various contaminants are produced during the cooking process which affect IAQ and comfort level for occupants. These contaminants are mostly produced from gas combustion and cooking, for example, polycyclic aromatic hydrocarbons, aldehydes, CO, NO_2, SO_2, oil smoke, particulates and heat, etc [2]. The less harmful products of gas combustion, namely, Water vapour and CO_2 are also produced in large amounts. It is necessary to maintain good IAQ and comfort levels for occupants and ventilation systems are incorporated in the kitchen to achieve this. In domestic kitchens, the ventilation system includes an Extraction hood, air-inlets and air conditioning units [3]. The Extraction hood is usually situated above the range cooker or sometimes mounted as a ceiling unit. In the extraction process, an amount of air containing cooking contaminants is exhausted via the hood in a bid to maintain a desired IAQ and comfort level within the kitchen areas. A supply of air is required to replace this exhausted air to maintain pressure within the kitchen area. There must always be a balance between the amount of air mass leaving and the amount entering a space. This supply of air mass, known as make-up air [3], depending on its source parameters, affects the air flow in the room and this influences the contaminant distribution within the room and consequently the performance of the extraction system [4, 5].

Although CO_2 is not a harmful product of gas combustion and human activity, its presence in high amounts is a clear indication of the performance (or poor performance) of a ventilation system [3]. The presence of high amounts of CO_2 is also an indication that other contaminants, for example CO, NO_2, SO_2, may also be present at high and harmful levels of concentration [2]. CO_2 is the most easily detectable compound compared to the other contaminants mentioned. The successful removal of CO_2 to the recommended or desired level indicates that the other contaminants are also extracted to a level that is not harmful to humans.

Previous studies have shown the effects of types of air-inlets on the dispersion of contaminant concentrations in confined spaces. However, these studies were performed for office spaces and very large enclosed areas, for example shopping centres. The studies have also used tracer gas to introduce the contaminant. The purpose of this research is to investigate the effect of air-inlet sizes and their locations on the ventilation process in domestic kitchens with gas burners during a realistic cooking process.

2 FLUENT AIRPAK

The flow field during the cooking process in the kitchen has been modelled using software package FLUENT Airpak 3.0.12 (see fig 1). Airpak is an accurate, quick, and easy-to-use design tool that simplifies the application of state-of-the-art airflow modeling technology to the design and analysis of ventilation systems which are required to deliver IAQ, thermal comfort, health and safety, air conditioning, and/or contamination control solutions [8]. Airpak uses the FLUENT CFD solver for thermal and fluid-flow calculations. The Airpak package includes – the tool for modeling, meshing and post processing and also FLUENT, the solver engine. Airpak solves the mass, momentum, species, and energy conservation equations. Additional transport equations are solved when the flow is turbulent [8]. The equations solved in the software are as follows:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\sigma_{ij}+F_i$$ (Momentum Equation) … (2.1)

Where

$$\sigma_{ij}=-p\delta_{ij}+\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$ (Newtonian Fluid) … (2.2)

Where $\delta_{ij}=\begin{cases}0, & when\ i\neq j\\ 1, & when\ i=j\end{cases}$

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0$$ (Continuity Equation) … (2.3)

Where u_i is the fluid velocity, σ_{ij} is the stress, p is the pressure, F_i is the body force and μ is the fluid viscosity.

The Reynolds stress is introduced by considering the time average of the fluid dynamics equations above.

For steady, incompressible flow without body forces, the Reynolds Averaged Navier-Stokes (RANS) equations solved is [7]:

$$\rho U_k\frac{\partial U_i}{\partial x_k}=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 U_i}{\partial x_j\partial x_j}+\frac{\partial\tau_{ij}}{\partial x_j}$$ (RANS Equation) … (2.4)

Where $\tau_{ij}=-\overline{\rho u_i u_j}$, the Reynolds stress.

The RANS equations require closure for the Reynolds stresses. The k-e model has been used in the present analysis.

Airpark solves the following energy equations simultaneously in the flow regions to yield a fully coupled conduction/convection heat transfer prediction.

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho h u_i)}{\partial x_j}=\frac{\partial}{\partial x_i}\left((k+k_t)\frac{\partial T}{\partial x_i}\right)+S_h$$ (Energy transport) … (2.5)

$$\frac{\partial}{\partial t}(\rho h)=\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+S_h$$ (Conduction) … (2.6)

Where k is the molecular conductivity, $k_t=\frac{c_p\mu_t}{\Pr_t}$ is the conductivity due to turbulent transport, T is temperature, ρ is density, h is enthalpy and S_h is the volumetric heat source.

The general conservation equation used for solving species transport is stated below:

$$\frac{\partial}{\partial t}(\rho Y_{i'})+\frac{\partial}{\partial x_i}(\rho u_i Y_{i'})=-\frac{\partial}{\partial x_i}J_{i',i}+S_i$$ (Species transport) … (2.7)

where $S_{i'}$ is the rate of creation by addition from user-defined sources, $J_{i'}$ is the diffusion flux of species, *i'* and $Y_{i'}$ is the local mass fraction of each species. An equation of this form will be solved for N-1 species where N is the total number of fluid phase species present in the system.

3 The model kitchen

For the analysis purposes the model kitchen space has been divided into three zones because three distinct flow patterns are observed within the kitchen flow field. These zones are the cooking zone, the breathing zone, and the room zone [6].

The cooking zone contains the space covering the gas range cooker and the extraction hood, while the breathing zone is defined as the space which people are most likely to occupy during the cooking period. This is the perimeter around the cooking zone of about 0.6m dimension .The room zone is the rest of the room space (See fig 1).

The kitchen modelled has dimensions of 4m x 4m x 2.4m (L x W x H) and includes an extraction hood with a specified dimension and fan characteristic curve. This dimension was chosen because it represents the average size of a typical domestic kitchen. The gas range cooker burners were modelled as a 5kw heat and CO_2 source and a pan was modelled as a steam source to simulate boiling water in a sauce pan. A calculated rate of production of CO_2 and H_2O was assigned to the heat and steam source respectively. The variables in the analysis were flow, temperature, radiation and species concentration. A high pre-determined level of CO_2 well above recommended levels was set as the initial conditions along with corresponding temperature and pressure, and transient simulations were run for 15-20 minutes for each air-inlet size and location. The CO_2 concentration within the breathing zone was observed to understand the efficiency of the extraction process. The following air-inlet sizes and locations described below were chosen for the investigation.

Air-inlet size 1 – 0.15m x 0.15m square

Air-inlet size 2 – 0.3m x 0.3m square

Air-inlet size 3 – 0.6m x 0.6m square

All these inlets were located at the side wall (see fig 1). After getting an optimum size, simulations were repeated at three locations with the optimum air-inlet size. These locations are given below.

Air-inlet location 1 – side wall

Air-inlet location 2 – above hood

Air-inlet location 3 – ceiling centre

The above sizes and locations were chosen from the various tested scenarios and represent categories of performance brackets.

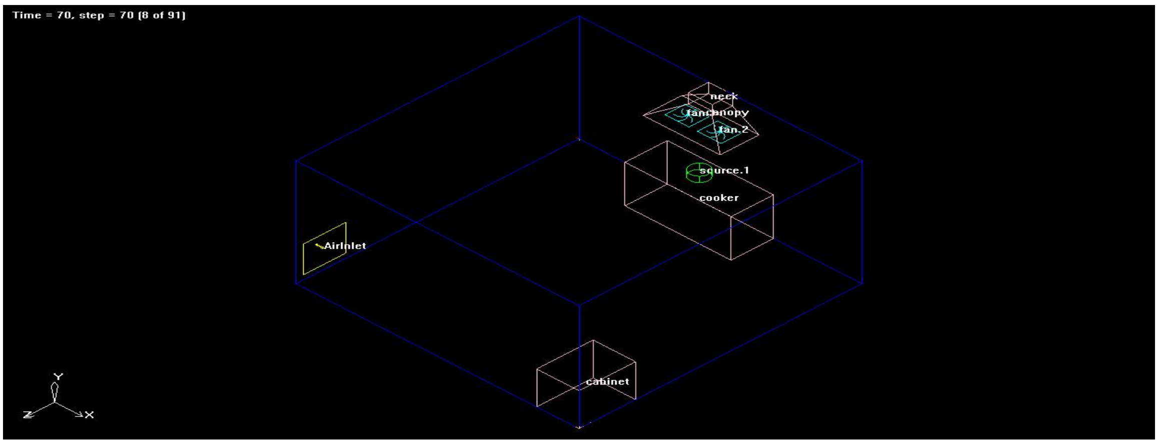

Fig1 – wire frame image of modelled kitchen showing a cabinet, the range cooker and a heat and steam source, a range hood and an air-inlet located on the side wall. The breathing zone is a perimeter, 0.6m around the range cooker.

4 Results

The following results were obtained from the flow field simulations carried out with the above mentioned air-inlet sizes and locations. The recommended level of CO_2 concentration in occupied spaces is 0.0018kg/m^3 which is equivalent to 1000ppm (parts per million) [3]. The CO_2 concentrations were observed within the breathing zone for different flow conditions. The three air-inlet sizes were investigated for one location, and the optimal air-inlet size was then used to investigate the two other locations.

The effect of the air-inlet size on extraction efficiency:

Figure 2 below shows a plot of CO_2 concentration over 20 minutes for an air-inlet size of 0.6 x 0.6m located on the side wall (see fig 1). It can be seen from the figure that the CO_2 concentration is at a maximum at time 0s which then reduces to a very low concentration by time 800s. Figure 3 shows another history plot of CO_2 concentration for an air-inlet size of 0.3 x 0.3m, also located on the side wall. It can be seen that the drop in CO_2 concentration is not as smooth as seen in figure 2. The CO_2 concentration reduction fluctuates considerably even after 800s in this particular case. Figure 4 shows another history plot for an air-inlet size of 0.15 x 0.15m on the same location. It shows a considerable fluctuation in CO_2 concentrations within the breathing zone and even after 800 seconds high concentrations of CO_2 are present. It can be concluded from the above observations that, a reduction in air-inlet size increases the time it takes to reduce the CO_2 concentration within the breathing zone to a value below the recommended level.

Figure 5 shows the velocity vector in the flow field for an air inlet size of 0.15mX0.15 m at 70s after the start of extraction. This figure shows the effects of the incoming air on the flow field. The magnitude of the incoming air speed is indicated by the colouring of the vectors with a maximum speed shown as red. Figure 5 also shows the direction and the path taken by the incoming air. The smaller the air-inlet is, the greater the speed of air that enters the room. This complicates the flow pattern inside the kitchen. Firstly, there is an introduction of a high current which can be experienced as draught by the occupants. Secondly, this high current produces the side-draught that blows the plume of CO_2 away from the hood, thereby hampering the extraction process. Thirdly, as figure 5 shows, with a strong current, the incoming air does not have a chance to mix with the rest of the room air before being removed from the room via the hood. Without complete mixing of the incoming air, there will not be the gradual dilution and removal of CO_2 and local pockets of CO_2 will form in the room which will be difficult to remove efficiently.

As seen in figure 2, which has a large air-inlet, the slow incoming air allows complete mixing of CO_2 resulting in the smooth reduction of CO_2 concentration. As the air-inlet size gets smaller, complete mixing is prevented and the CO_2 concentration never reduces in some areas of the room. Pockets of CO_2 are moved around the room due to the swirls created in some areas of the room by the stronger current of incoming air. This causes the spikes in CO_2 concentrations within the breathing zone as seen in figure 3. This effect is even more pronounced for the smallest air-inlet size used, as seen in figure 4. Fourthly, as the air-inlet gets smaller, there is a build up of negative pressure within the room. This could be a dangerous situation because of the presence of various kitchen appliances and other installations, for example, central heating boilers. The negative pressure can cause harmful gases to seep in to the room creating unfavourable conditions within the living space.

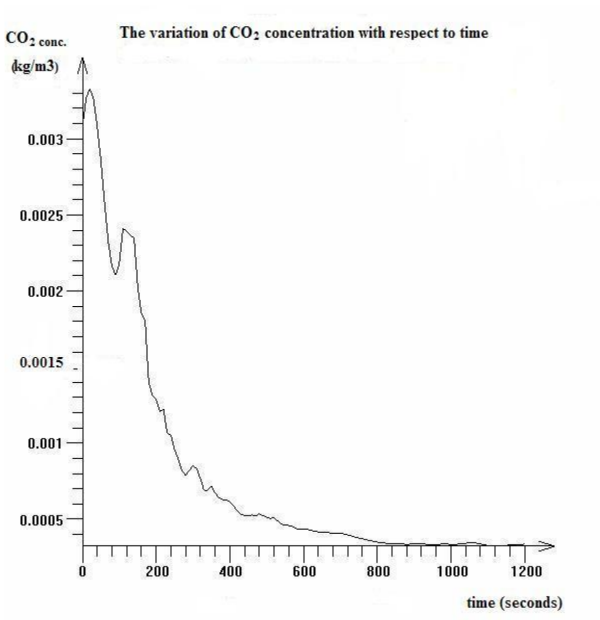

Fig2 – The variation of CO_2 concentration with respect to time for an air-inlet size of 0.6 x 0.6m, located on the side wall

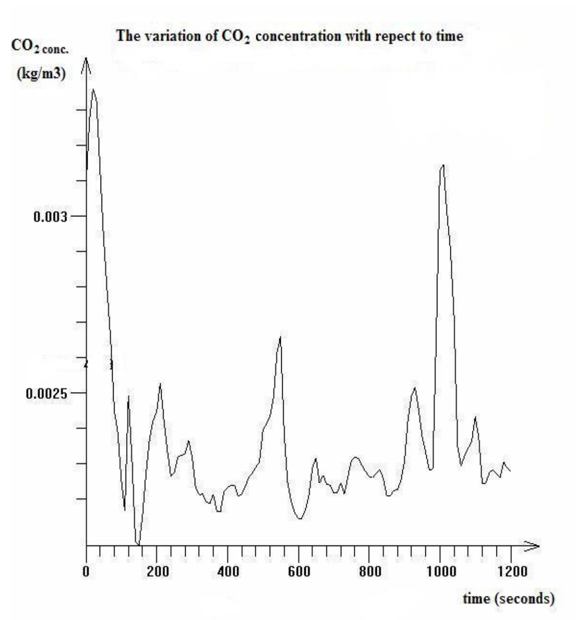

Fig4 – The variation of CO_2 concentration with respect to time for an air-inlet size of 0.15 x 0.15m, located on the side wall

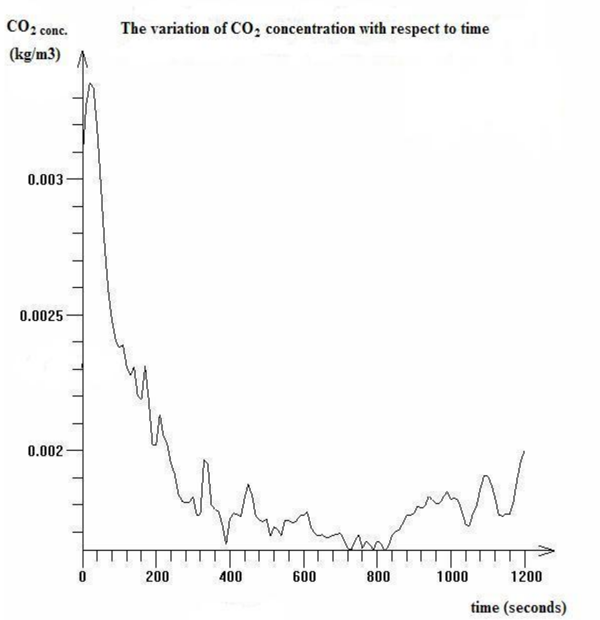

Fig3 – The variation of CO_2 concentration with respect to time for and air-inlet size of 0.3 x 0.3m, located on the side wall

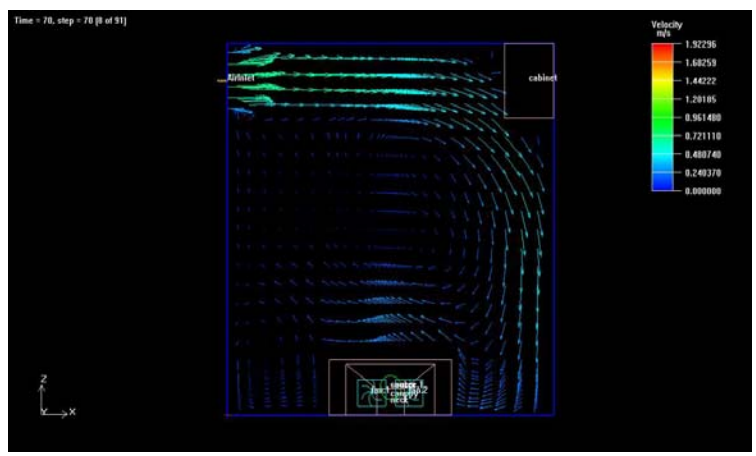

Fig5 – plane cut of velocity vector at time 70s, showing the air flow in the room produced by incoming air from the air-inlet. Red indicates maximum velocity.

The effects of air-inlet locations on extraction efficiency:

As observed above, the larger the air-inlet the slower the air coming into the room and therefore the better the complete mixing of new clean air with the room air which enhances the overall room extraction of CO_2. Apart from this, the location of the air-inlet can also have great influence on extraction efficiency

Figure 6 shows the CO_2 concentration for an air-inlet of area of $0.36m^2$ located at the centre of the ceiling. This shows that a region near the ceiling of the model kitchen has high concentrations of CO_2 even after 900s. Figure 7 shows the CO_2 concentration for an air-inlet of the same area located at the side wall near the floor of the model kitchen. This figure shows a band of high concentration of CO_2, but the colour of the band indicates that the concentration of CO_2 present is less than that observed in figure 6. This figure also shows a break in the plume indicating that this location of air-inlet produces side-draught. Figure 8 shows CO_2 concentration for the air-inlet of the same area located above the hood. This also shows the band of high CO_2 concentration near the ceiling, but at much less concentrations than observed in both figures 6 and 7. Figure 8 represents the optimal location of air inlet for this investigation that allows for the complete mixing of the room air with the incoming air. As the air-inlet is located above the hood, any escaped CO_2 is immediately mixed with the incoming fresh air and then distributed evenly throughout the room enhancing complete mixing.

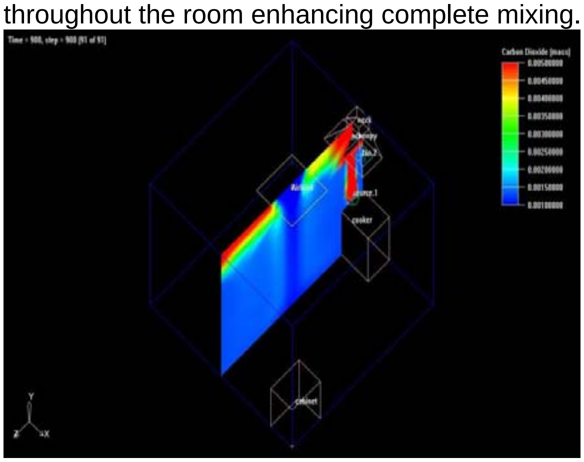

Fig6- Plane cut CO_2 conc. Contour at time 900s, air-inlet located at ceiling centre

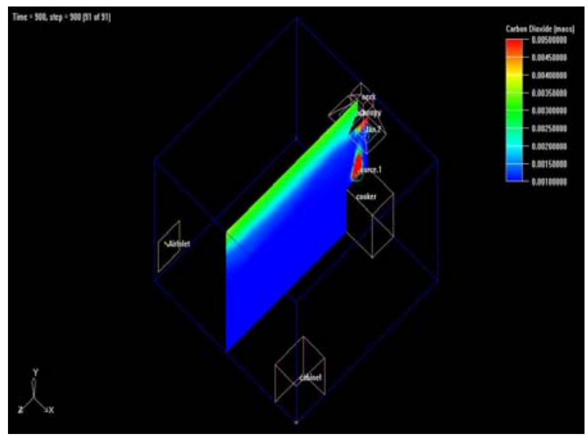

Fig7- Plane cut CO_2 conc. Contour at time 900s, air-inlet located at side wall

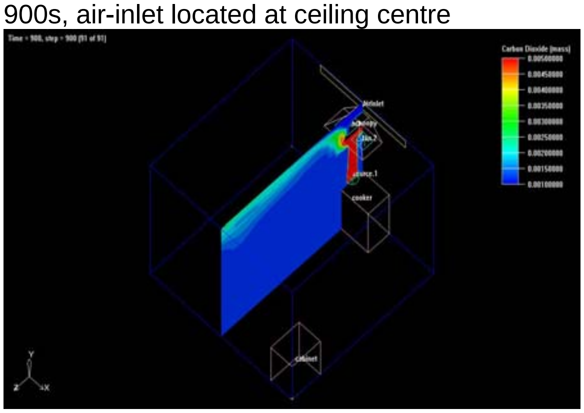

Fig8- Plane cut CO_2 conc. Contour at time 900s, air-inlet located above hood

5 Conclusions

- In a kitchen an appropriately sized air-inlet is required to:
  1. Reduce negative pressure build up,
  2. Maintain a draught free room with maximum recommended room velocity of 0.25m/s and
  3. Provide complete air mixing in the room which enhances the CO_2 extraction process
- Air-inlet location effects both local (cooking zone) and global extraction (breathing and room zones)
- Depending on the location of the air-inlet, Side-draught can be experienced, effecting the plume flow direction and inhibiting local extraction.
- Depending on the location of the air-inlet, incomplete room air mixing of contaminants can occur.
- The location that produces best performance is the one above the hood.

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