393: The Effect of Urban Micrometeorology on Indoor Living Conditions

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Abstract

The urban climate has an altering effect on the living conditions of its human inhabitants. Altering the indoor climate to a desired level of comfort is a key contributor to building energy use. Predicting this demand requires an accurate building heat balance simulation tool and components of this heat balance may be affected by the building's micrometeorology. Infiltration is defined as the unintentional flow of air from outdoors directly into a building. This component of the indoor heat balance is directly influenced by the pressure forces exerted on the building exterior by wind therefore understanding the wind profiles around a building is crucial to modelling infiltration. Experimental work is presented in which a dataset of infiltration rates as well as indoor temperature and were measured in a single thermal zone within an urban building simultaneously to local meteorological measurements. Full scale data sets such as this are crucial for model validation.

Keywords: infiltration, heat balance, indoor temperature, experimental

1. Introduction

The UK Climate Change Risk Assessment [1] highlights overheating of buildings within the built environment as an area of high future risk. Higher indoor temperatures lead to increasing energy demand for building cooling and poor thermal comfort reduces productivity [2] and can be fatal. During the 2003 heat wave a 33% rise in heat stress related deaths was observed in London [3].

In order to describe and model the overheating of buildings within cities and the thermal comfort of their occupants it is necessary to understand all the processes which contribute to the heat balance of an indoor environment. Principally these are direct solar gain, conduction through exterior facets and indoor-outdoor air exchange.

Infiltration is defined as the unintentional flow of air from outdoors to indoors through cracks in the building fabric. The rate of infiltration is controlled by the pressure difference across these cracks and the pressure at the exterior facet is driven by the local wind. Understanding how infiltration responds to wind conditions on a sub-daily time scale is crucial for predicting indoor temperature peaks but in-situ datasets of infiltration rates alongside wind for validation of mathematical models are limited.

The principal aim of this work was therefore to establish a data set which could be used to test mathematical models of building infiltration and heat balance simulations as a whole within an urban setting.

2. Modelling Considerations

The principal program to be used is EnergyPlus [4]. EnergyPlus was developed by the US DOE and based on the previous success of the BLAST and DOE-2, both of which are used as reference programs for testing other simulations. This program is used because it is a freely available and widely used research tool that compares well with others [5].

Infiltration is described empirically in EnergyPlus using coefficients which take default values or are specified by the user. The most straightforward formulation is the design flow rate:

$$Infiltration = (I_{design})(F_{schedule})[A + B|\Delta T| + C.U + D.U^2] \quad (1)$$

where I_{design} is the design flow rate, $F_{schedule}$ a user defined schedule value (accounting for human activity), U the local wind speed, ΔT the temperature difference between zone and outdoor air and A, B, C and D are coefficients. Infiltration is given in air changes per hour.

The wind speed used is that at the mid zone height calculated using a power law wind profile, therefore the primary simplifications made by equation 1 are that the wind speed in an urban area can be described by a power law and that the profile around the building is not dependent upon the wind direction. The same simplifications are made by the other formulations in EnergyPlus.

The next section describes experimental work undertaken to measure infiltration rates alongside indoor temperature and local meteorological measurements. This is followed by some results and considerations of how these will be used alongside results from wind tunnel simulations for comparison with theory.

2. Experimental Methods

2.1 Outline

The mass balance of a thermal zone (a single large room) was completely measured, including air exchange rates with neighbouring zones. The principal output of any heat balance simulation is a time series of indoor temperatures and so these were also measured for comparison. A rooftop site recorded meteorological data.

The experimental work was carried out over a seven week period from 24th November 2011 to 12th January 2012.

2.2 Location

The test building was the Westminster City Council (WCC) building on Marylebone Road in Westminster, central London (51.5213^0N, 0.1604^0W). Marylebone Road is a busy thoroughfare approximately 1.2 miles in length, running ESE-WNW with three lanes of traffic travelling in each direction. The WCC building lies close to the intersection with Gloucester Place, which runs approximately north-south. This building has 4 floors above ground and is 15 m in height above street level. Wood *et al.* [6] gave the mean building height for the surrounding area as 21.5m. Figure 1 shows an aerial photograph of the building and locality.

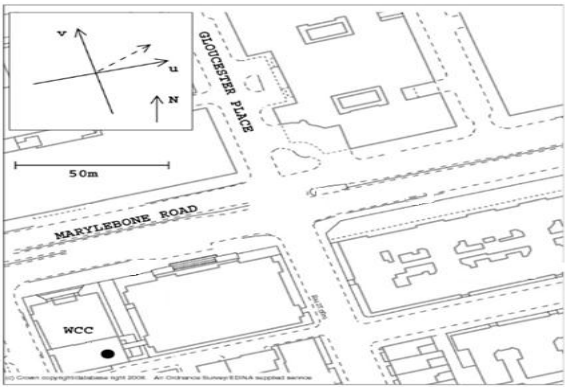


Fig 1. Aerial photograph showing the WCC building and the Marylebone Road – Gloucester Place intersection.

A meteorological observation station consisting of a Gill R3 sonic anemometer, Licor Li-7500 infra-red hygrometer, Kipp and Zonen CNR4 net radiometer and Vaisala WXT520 weather station was mounted on a 3m mast on the rooftop.

The room in which indoor monitoring was carried out was on the top floor and had exterior walls overlooking the Marylebone Road street canyon and the building's courtyard. Its floor area is 117 m^2 and approximate volume 364 m^3.

2.3 Methods

The indoor monitoring consisted of three parts; NO_X levels, tracer gas decays and temperature profiling.

To monitor NO_X ($NO + NO_2$) levels sampling tubes were placed immediately outside the exterior walls overlooking Marylebone road and the courtyard. The tubes were fed through sealed holes in window frames back to a gas analyser inside the room. A third sampling tube was placed at the centre of the room so indoor and outdoor conditions could be compared. Figure 2 shows the sampling locations. The gas analyser takes 3 minutes to sample each tube and so works on a 9 minute cycle. Because wind direction and speed are averaged over 30 minute periods a 9 minute resolution in NO_X concentrations is high enough for comparison.

The tracer gas decay test was carried out by releasing an inert tracer gas from multiple points around the walls of the main room, the adjacent kitchen, corridor and room 65 (also adjacent). Gas sampling tubes were placed within each location at a point at which the air was able to flow across the end of the tube. The locations of these are shown in figure 2. Tubes were collected and replaced weekly.

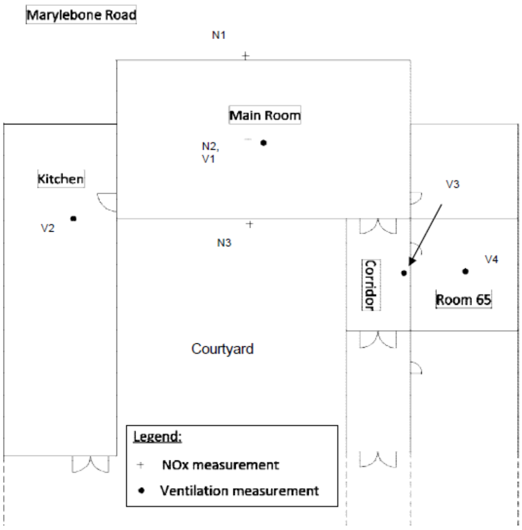


Figure 2 – Schematic showing the locations of the NO_X sampling points N1-N3 and tracer decay tubes V1-V4.

Temperature profiling was done by placing masts at five locations within the main room, one close to each corner (1.5m from each wall) and one by the central table on which the tracer decay tube and NOX tube were placed. 3 Tinytag ultra2 data loggers were mounted on each mast at 0.1m, 1.1m and 1.7m, the height at which thermal comfort should be measured according to ASHRAE standard 55-2010. An additional logger is placed beneath the center of the room beneath the peak of the domed ceiling at a height of 3.3m. Temperature and Relative Humidity were logged every minute.

2.4 Extracting Infiltration Rates from NO_X Measurements by Inverse MIAQ Method.

In the following section results are presented from an attempt to assess the infiltration rates during November 28 2011 using the NO_X measurements. Theoretical simulations were conducted with the aid of the well-known indoor air quality model MIAQ (Multichamber Indoor Air Quality model). MIAQ is a general mathematical model for concentrations of chemically reactive compounds in indoor air [7]. It accounts for the effects of ventilation, infiltration, direct emission, deposition onto surfaces, and chemical (both thermal and photochemical) reactions. Model results have been repeatedly validated with experimental data [6, 7]. The measured outdoor NO and NO_2 concentrations, and the geometric characteristics of the indoor surfaces were set as inputs to the model. Then, consecutive numerical experiments with varying infiltration rates were conducted, until the hourly indoor concentrations calculated by the model were equal to the indoor measured ones. In the past similar methods have been successfully used in order to indirectly estimate the ventilation and particulate production rates in various microenvironments [8, 9].

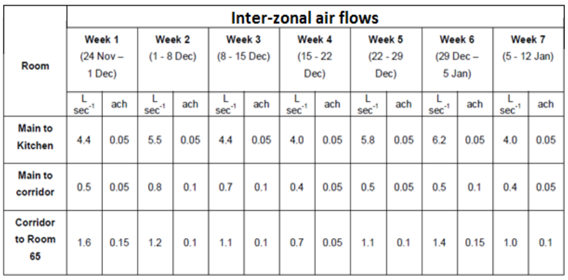
The NO and NO_2 concentrations were measured in the immediate outdoor environment. O_3 outdoor concentrations were obtained by a nearby monitoring station. Typical deposition rates were obtained from literature [10].

During the numerical experiments, the following processes were taken into account: transport from outdoors to the indoor environment, transport from the indoor to the outdoor environment, deposition on indoor surfaces, and the main photochemical reactions

$$\begin{aligned} &NO_2 + hv \rightarrow NO + O(^3P) \\ &O(^3P) + O_2 + M \rightarrow O_3 + M \\ &O_3 + NO \rightarrow NO_2 + O2 \end{aligned} \qquad (2)$$

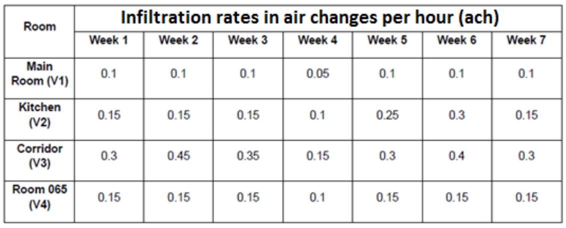
3. Results

Laboratory analysis of the tracer gas tubes was performed by the BRE. Results were produced for inter-zonal flows along with infiltration rates from each zone. These are presented in tables 1 and 2.



Room	Inter-zonal air flows													
	Week 1 (24 Nov – 1 Dec)		Week 2 (1 - 8 Dec)		Week 3 (8 - 15 Dec)		Week 4 (15 - 22 Dec)		Week 5 (22 - 29 Dec)		Week 6 (29 Dec – 5 Jan)		Week 7 (5 - 12 Jan)	
	L sec^{-1}	ach	L sec^{-1}	ach	L sec^{-1}	ach	L sec^{-1}	ach	L sec^{-1}	ach	L sec^{-1}	ach	L sec^{-1}	ach
Main to Kitchen	4.4	0.05	5.5	0.05	4.4	0.05	4.0	0.05	5.8	0.05	6.2	0.05	4.0	0.05
Main to corridor	0.5	0.05	0.8	0.1	0.7	0.1	0.4	0.05	0.5	0.05	0.5	0.1	0.4	0.05
Corridor to Room 65	1.6	0.15	1.2	0.1	1.1	0.1	0.7	0.05	1.1	0.1	1.4	0.15	1.0	0.1

Table 1 – Inter-zonal flow rates across each boundary between the zones tested in the WCC building. Values ±0.1 Ls^{-1} or ±0.05 ach.



Room	Infiltration rates in air changes per hour (ach)						
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Main Room (V1)	0.1	0.1	0.1	0.05	0.1	0.1	0.1
Kitchen (V2)	0.15	0.15	0.15	0.1	0.25	0.3	0.15
Corridor (V3)	0.3	0.45	0.35	0.15	0.3	0.4	0.3
Room 065 (V4)	0.15	0.15	0.15	0.1	0.15	0.15	0.15

Table 2 – Infiltration rates for each of the 4 indoor zones tested in the WCC building. All values ±0.05 ach.

These results show that there is very little variation in the weekly averaged infiltration rates. All 4 zones show a minimum value for week 4 which is attributed to snowfall during this week. Snowfall alters thermal gradients and partially covers cracks in building fabric.

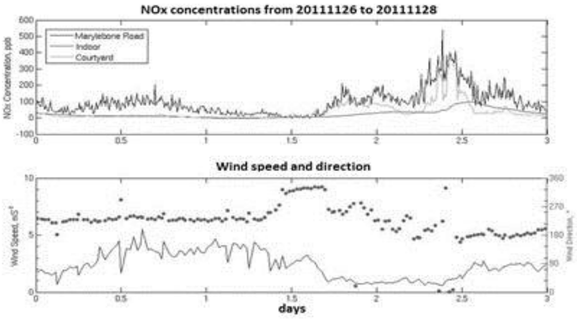


Figure 3 – Indoor and outdoor NO_X concentrations (top) from measurements taken at WCC building and wind speed and direction (bottom) from rooftop met mast. Time axis in days starting 26th Nov 2011.

Figure 4 – Infiltration rates for room 1 on 28th Nov 2011 calculated from NO_X data using inverse MIAQ method.

The NO_X results produced a time series of concentrations which can be compared to meteorological conditions, particularly wind. The prevailing wind direction during the observation period was south-westerly, as is usual for England. The mean wind speed was 2.42 ms^{-1} with a standard deviation of 0.92 ms^{-1}.

Figure 3 shows the indoor and outdoor NO_X concentration time series for a selected period of three days from 26th – 28th Nov 2011 plotted in line with the wind speed and direction time series. The wind conditions are initially south westerly but northerly winds were observed on the morning of the 28th after a drop in wind speed on the night of the 27th. The effect of the changing wind conditions can be seen in the NO_X results, with a much higher concentration building up in the canyon during the 28th with a peak in the courtyard concentrations coinciding with the northerly winds. These rises in levels outside both exterior walls are followed by a peak in indoor concentration with a time lag of approximately 2 hours.

The inverse MIAQ method has been used to produce infiltration rates for the main room for the 28th Nov and these are shown in figure 4. A rough check between the methods looks promising; the weekly mean was 0.1 ach which converts to 0.6 m^3min^{-1} and this compares well to figure 4. The higher resolution results illustrate how infiltration may vary on a sub daily time scale.

Investigating the magnitude of these variations and the contribution to the heat balance of the indoor climate is a future aim as discussed in the next section.

The thermal profiling produced a time series of indoor temperatures. The variation of indoor temperature with time was limited due to the high thermal mass of the building and because the outdoor diurnal variations were less during this winter time IOP than they would have been expected to be in summer, hence giving some motivation to repeat the work at a different time of year. EnergyPlus assumes air within a zone is well mixed and so the volume average will be used for comparison.

4. Future Work

4.1 Wind Tunnel

A 1:200 scale model of the area around the Marylebone Road and Gloucester Place intersection existed from previous work on pollution dispersion in this area (DAPPLE project) at the EnFlo laboratory at the University of Surrey [11].

Work is planned to measure the pressure forces exerted on the building facets by varying wind direction. These results can be used to improve estimation of infiltration as a function of wind.

4.2 Modelling

Experimental results will be compared with mathematical models in the literature. A detailed EnergyPlus simulation of the case study building will be developed and run using a weather file made from rooftop observations. This will be used to test whether increasing the accuracy of infiltration estimates makes a significant improvement to the accuracy of the overall heat balance calculations.

5. Conclusion

The methodology in collecting a dataset of full scale infiltration measurements of infiltration and indoor temperature has been described. Two methods were used to calculate infiltration at high and low time resolution. Initial results show good agreement between methods. The experimental work was designed to test mathematical models of infiltration as a function of wind and to test how important correct estimation if infiltration is to the heat balance of a building.

6. Acknowledgements

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