Performance of domestic ventilation systems: A simulation study

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ABSTRACT

Multi zone computer simulation is used to predict the concentrations of carbon dioxide, carbon monoxide, formaldehyde and water vapour in a flat and detached house, fitted with five different ventilation systems all of which comply with current building regulations for England and Wales. Results show that, understandably, the different ventilation systems produce different spatial and temporal pollutant concentrations. A method based on equivalent ventilation rates for each pollutant is used to optimise the specification of the ventilation systems.

1. INTRODUCTION

This paper reports on a study using computer simulation to investigate and compare the performance of five domestic ventilation systems, designed in accordance with Approved Document Part F (HMSO 2006) of the building regulations of England and Wales. The systems were compared in terms of the predicted room-by-room concentration-time profiles of four pollutants and by comparison with appropriate guideline levels.

The study comprises of annual simulations on an hourly basis for a detached house and a flat, using the multi-zone ventilation model CONTAMW 2.1 (Dols 2002). Two dwelling types were studied: a mid-floor flat with two external façades, and a detached house, both with an air permeability of $3m^3.hr^{-1}.m^{-2}$.

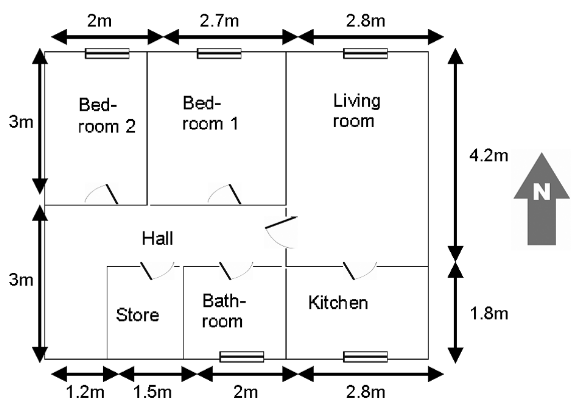

Figure 1. Floor plan of Flat

The geometry and floor plans of the modelled dwellings are shown in Figures 1and 2.

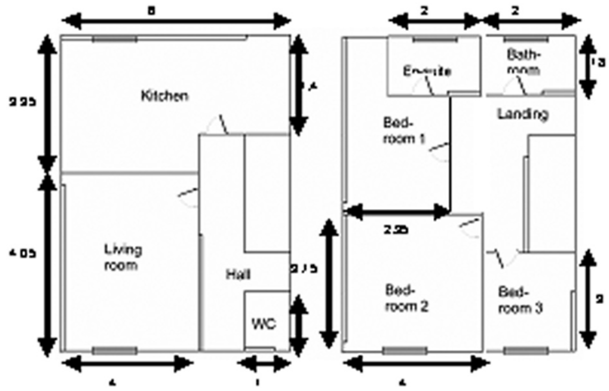

Figure 2. Floor plan of detached house.

For both the flat and the detached house, the ventilation systems studied in this project were:

1. Base case – trickle vents & intermittent extract
2. Continuous mechanical extract
3. Continuous mechanical supply
4. Balanced mechanical supply and extract
5. Passive stack ventilation

Details of the ventilations systems are given in Figure 7.

Location	Occupancy
Living room	1 adult 17:00 – 18:00, 18:30 – 19:30, 21:30 – 22:00
	2 adults 19:30 – 21:30
	2 children 17:00 – 19:30, 20:30 – 21:30
	1 child 19:30 – 20:30
Bedroom 1	2 adults (asleep) 23:00 – 07:00
	1 adult 07:00 – 07:45
	2 adults 22:00 – 23:00
Bedroom 2	1 child 13 yrs (asleep) 22:00 – 07:30
	1 child 13 yrs 07:45 – 08:00
	1 child 13 yrs 21:30 – 22:00
Bedroom 3	1 child 12 yrs (asleep) 22:00 – 07:30
	1 child 12 yrs 07:30 – 7:45
	1 child 12 yrs 21:30 – 22:00
Bathroom	1 child 07:30 – 08:00, 19:30 – 20:30

En-suite	1 adult	07:00 – 07:30, 21:30 – 22:00
Kitchen	1 adult	07:30 – 07:45, 08:15 – 08:30, 18:00 – 19:30
	2 adults	07:45 – 08:15
	1 child	08:00 – 08:15
	2 children	08:15 – 08:30

Figure 3. Occupancy pattern of

Location	Occupancy	
Living room	1 adult	17:00 – 18:00, 18:30 – 19:30, 21:30 – 22:00
	2 adults	19:30 – 21:30
	2 children	17:00 – 19:30, 20:30 – 21:30
	1 child	19:30 – 20:30
Bedroom 1	2 adults	23:00 – 07:00 (asleep)
	1 adult	07:00 – 07:45
	2 adults	22:00 – 23:00
Bedroom 2	2 children	22:00 – 07:30 (asleep)
	1 child	07:30 – 0815
	2 children	21:30 – 22:00
Bathroom	1 adult	07:00 – 07:30, 21:30 – 22:00
	1 child	07:30 – 08:00, 19:30 – 20:30
Kitchen	1 adult	07:30 – 07:45, 08:00 – 08:30, 18:00 – 19:30
	2 adults	07:45 – 08:00
	1 child	08:00 – 08:15
	2 children	08:15 – 08:30

Figure 4 Occupancy pattern of flat

To take account of interventions by the occupants such as window and internal door opening a series of patterns of building occupancy were developed, Figures 3 and 4. Two key scenarios were investigated: little use of windows for airing and internal doors typically closed, extensive use of windows and internal doors frequently open. Four types of pollutant emission profiles were considered:

a) continuous constant emission – this was modelled by assuming emission of formaldehyde in all rooms on a floor area-weighted basis;

b) localised ‘event’ based constant emission during limited time periods – ie carbon monoxide generated by gas cooking;

c) occupant generated bio effluents – for this we used CO_2 concentrations as a surrogate tracer, with emission rates according to occupancy;

d) moisture – this is generated by occupants and their activities, such as cooking, washing, and showering.

The background outdoor level of formaldehyde was assumed to be constant at 2 $\mu g.m^{-3}$. A room-by-room total emission rate of formaldehyde of 250$\mu g.h^{-1}m^{-2}$, normalised by floor area is assumed. CO emission rate in the kitchens during cooking periods was, 0.04 $mg.s^{-1}$ from 18:00-19:00 and 0.70 mgs^{-1} from 19:00-19:30. The background level of CO was assumed to be constant at 0.469 $mg.m^{-3}$. The background level of CO_2 was set at a constant 730 $mg.m^{-3}$ (400 ppm). The carbon dioxide emission rates of an adult were assumed to be 18 l/hr when awake and 12 l/hr when asleep, and for a child 12 l/hr when awake and 8 l/hr when asleep. Moisture production rates, from breathing, cooking, bathing and clothes washing were based on data from British and European sources (BS 5250, 2002, ECBS Annex 27), these are given in Figures 5 and 6. Annual simulations were performed using a London (Kew.TRY) weather file.

F1 Vents & Intermittent mechanical extract

Vent equivalent areas
(for above window trickle vents)
Bedroom 1: 10000 mm²
Living Room, Kitchen: 12500 mm² in each room
Bedroom 2, Bathroom: 7500 mm² in each room
Total: 50000 mm²
Intermittent mechanical extract, week day
Kitchen : 60 l/s (07:30 to 08:30 and 18:00 to 19:30)
Bathroom: 15 l/s (07:00 to 08:00, 19:30 to 20:30 and 21:30 to 22:00)
Intermittent mechanical extract, weekend
Kitchen : 60 l/s (08:30 to 09:30, 12:00 to 12:30 and 18:00 to 19:30)
Bathroom: 15 l/s (08:00 to 09:00, 19:30 to 20:30 and 21:30 to 22:00)

F2Continuous mechanical extract

Vent equivalent areas
(for above window trickle vents)
Bedroom 1, Bedroom 2, Living Room: 2500 mm² in each room
Continuous mechanical extract

Kitchen :	13 l/s	(no boost required)
Bathroom:	8 l/s	(no boost required)

F3Continuous mechanical supply

Continuous mechanical supply
Hall: 21 l/s from external (no boost required)

F4 Balanced mechanical supply and extract

Sensible heat recovery 90%
Whole building ventilation rate 21 l/s
Air infiltration (according to Part F assumption) 6.5 l/s

Continuous mechanical extract		
Kitchen :	9.0 l/s	(13 l/s boost)
Bathroom:	5.5 l/s	(8 l/s boost)
Continuous mechanical supply		
Living room:	6.2 l/s	(9 l/s boost)
Bedroom 1:	4.1l/s	(6 l/s boost)
Bedroom 2:	4.1l/s	(6 l/s boost)

System boost period, week day
07:00 to 08:30, 18:00 to 20:30, 21:30 to 22:00
System boost period, weekend 08:00 to 09:30, 12:00 to 12:30, 18:00 to 20:30, 21:30 to 22:00

F5 Passive stack ventilation

Vent equivalent areas
(for above window trickle vents)
Living Room: 20000 mm²
Bedroom 1: 15000 mm²
Bedroom 2: 10000 mm²
Total: 45000 mm²
Passive stack cross-sectional areas
Kitchen : 12000 mm²
Bathroom: 8000 mm²

Figure 7 : Specifications of modelled systems

H1 Base case – Vents & Intermittent Extract
Vent equivalent areas
(for above window trickle vents)
Bedroom 1, Living Room: 10000 mm² in each room
Bedroom 2, Bedroom 3, Kitchen, Bathroom, En-suite: 5000 mm² in each room
Total: 45000 mm²
Intermittent mechanical extract, week day
Kitchen : 60 l/s (07:30 to 08:30 and 18:00 to 19:30)
En-suite: 15 l/s (07:00 to 07:30 and 21:30 to 22:00)
Bathroom: 15 l/s (07:30 to 08:00 and 19:30 to 20:30)
Intermittent mechanical extract, weekend
Kitchen : 60 l/s (08:30 to 09:30, 12:00 to 12:30 and 18:00 to 19:30)
En-suite: 15 l/s (08:00 to 08:30 and 21:30 to 22:00)
Bathroom: 15 l/s (08:30 to 09:00 and 19:30 to 20:30)

H2Continuous Mechanical extract
Vent equivalent areas
(for above window trickle vents)
Bedroom 1, Bedroom 2, Bedroom 3, Living Room: 2500 mm² in each room
Continuous mechanical extract
Kitchen : 9.4 l/s (13 l/s boost)
En-suite: 5.6 l/s (8 l/s boost)
Bathroom: 5.6 l/s (8 l/s boost)
System Boost Period, Week Day
07:00 to 08:30, 18:00 to 20:30, 21:30 to 22:00
System Boost Period, Week End
08:00 to 09:30, 12:00 to 12:30, 18:00 to 20:30, 21:30 to 22:00

H3 Continuous Mechanical supply
Landing: 21 l/s (from loft space)

H4 Balanced mechanical supply and extract
Continuous mechanical extract
Kitchen : 5.2 l/s (13 l/s boost)
En-suite: 3.3 l/s (8 l/s boost)
Bathroom: 3.3 l/s (8 l/s boost)
Continuous mechanical supply
Living room: 4.5 l/s (11 l/s boost)
Bedroom 1: 2.4 l/s (6 l/s boost)
Bedroom 2: 2.4 l/s (6 l/s boost)
Bedroom 3: 2.4 l/s (6 l/s boost)
System boost period, week day
07:00 to 08:30, 18:00 to 20:30, 21:30 to 22:00
System boost period, weekend
08:00 to 09:30, 12:00–12:30, 18:00 to 20:30, 21:30 to 22:00

H5 Passive Stack Ventilation
Vent equivalent areas
(for above window trickle vents)
Living Room: 17500 mm²
Bedroom 1: 10000 mm²
Bedroom 2, Bedroom 3: 5000 mm² in each room
Total: 37500 mm²
Kitchen : 12000 mm²
En-suite: 8000 mm²
Bathroom: 8000 mm²

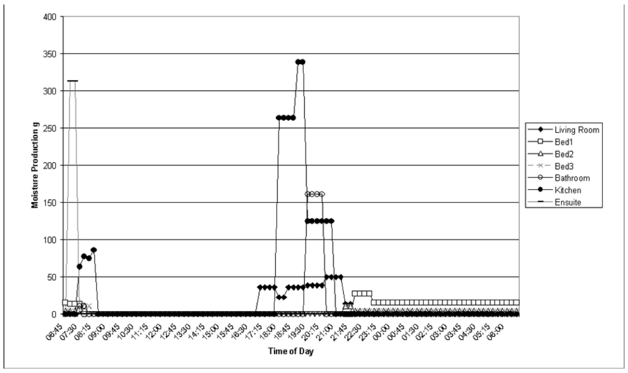

Figure 5 Moisture production schedule: house

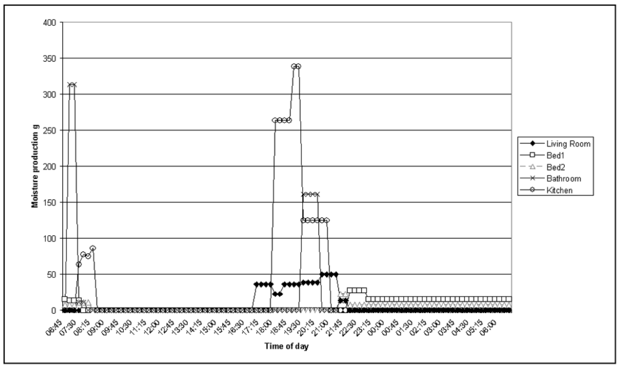

Figure 6 5 Moisture production schedule: flat

2. RESULTS

For brevity the results, Figure 8, are summarised here by presenting the whole dwelling average concentrations (volume weighted average of room concentrations) of the four pollutants during the heating season (October to May)

System	CO_2 ppm	CO mgm^{-3}	HCOH ugm^{-3}	RH%
F1	879	0.78	185	48.9

F2	864	1.31	140	57.2
F3	830	1.49	144	53.8
F4	975	1.36	177	54.2
F5	711	0.95	105	45.7
H1	628	0.8	212	46.4
H2	740	1.43	280	52.2
H3	749	1.19	253	55.1
H4	736	1.21	256	50.7
H5	823	1.56	343	52.9

Figure 8. Whole dwelling average concentrations of pollutant. Standard ventilation systems.

The results suggest that the five modelled systems result in different concentrations of pollutants. Installation of any of the systems in a dwelling results in compliance with building regulations, but because of the underlying differences between operating methods they understandably do not provide identical spatial and temporal levels of IAQ.

A number of metrics were investigated to describe the relative performance of the systems and out of these the 'equivalent ventilation rate' was judged as most suitable. The equivalent ventilation rate is defined as follows. On the assumption that the seasonal average volume weighted internal concentration $\overline{C}$ may be interpreted as a quasi-steady state concentration, we may define a so-called 'equivalent ventilation rate', Q_{eq}, for each system and pollutant, as follows:

$$Q_{eq} := \frac{\overline{q}}{\overline{C} - C_{ext}},$$

where $\overline{q}$ is the seasonal whole dwelling average internal emission rate of the pollutant (g.s^{-1}), C_{ext} is the assumed constant concentration of pollutant in the outdoor air (g.m^{-3}), and

$$\overline{C} = \frac{1}{M}\sum_{t=1}^{M}\left(\frac{\sum_{i=1}^{N} V_i C_{t,i}}{\sum_{i=1}^{N} V_i}\right)$$

with $C_{t,i}$ being the indoor concentration of the i^{th} of a total of N rooms in the dwelling (each with volume V_i) at the t^{th} discrete time step from a total of M in the whole season. The equivalent ventilation rate provided by each of the systems was computed and used to assess the likely changes in system specification that would 'optimise' the performance. Figure 9, below shows the volume weighted average (VWA) pollutant concentration and equivalent ventilation rates (EVR) for the flat based on formaldehyde, from building materials, as the pollutant. Note the seasonal concentration exceeds the World Health Organisation exposure limit, which for formaldehyde is 100 µg.m^{-3} based on a 30 minute exposure period.

System	VWA ug.m^{-3}	EVR l/s	EVR ach
F1	191	16.1	0.54
F2	137	22.8	0.76
F3	143	21.9	0.73
F4	177	17.7	0.59
F5	108	28.9	0.96

Figure 9. Equivalent ventilation rates and volume weighted average concentration of formaldehyde for each ventilation system. Average seasonal pollutant emission rate 3.13µg.s^{-1}

The equivalent ventilation rates for all the pollutants (except moisture) were then used to 'optimise' the systems. This optimisation required a clear distinction to be made between avoidable and unavoidable pollutants and the system types because of the manner in which the system and pollutant interacted. The optimisation phase of the study took the same modelling approach as in the first phase but with the system specifications 'optimised' to provide satisfactory and approximately equal levels of IAQ with respect to all the pollutant types, and to ensure that levels did not exceed, accepted guideline values. For formaldehyde, as an example of an avoidable pollutant, the emission rate was also reduced.

The following changes to the systems in the Flat were made:

a) Intermittent local extract fans – increased vent areas (+58%) with single vents
b) Intermittent local extract fans – increased vent areas(+58%) with high and low level vents
c) Continuous mechanical extract – increased vent areas (+133%) and boost mode (18l/s kitchen, 11 l/s bathroom) added
d) Central mechanical supply – local vents (47000mm^2) with 29 l/s boost mode added
e) Balanced mechanical ventilation – normal and boost modes increased (+38%)
f) Passive stack ventilation – stack heights increased by 50%
g) Passive stack ventilation – increased stack cross-sectional areas (+33%)
h) Passive stack ventilation - increased stack cross-sectional areas (+33%) with 10000mm^2 transfer grills on internal doors to habitable and wet rooms

The following changes to the systems in the House have been made:

a) Intermittent local extract fans – increased extract fan rate (30 l/s) in Bathroom and En-Suite
b) Intermittent local extract fans – increased vent areas (+100%) in all rooms
c) Intermittent local extract fans - increased vent areas in all habitable and wet rooms with 10000mm^2 transfer grills on internal doors
d) Continuous mechanical extract - increased vent areas (+125%) in all habitable rooms with normal and boost modes increased (+40%)

e) Central mechanical supply - local vents in rooms (55500mm^2) added with normal mode increased (+40%) and boost mode (40l/s) added
f) Balanced mechanical ventilation – normal mode increased (+38%)
g) Passive stack ventilation - increased stack cross-sectional areas (=33%) with transfer grills (10000mm^2) on internal doors to habitable and wet rooms.

	CO_2 ppm	CO mg.m^{-3}	HCOH µgm^{-3}	RH%
Fa	757	0.71	69	50.9
Fb	552	0.59	37	46.8
Fc	829	1.09	65	55.3
Fd	745	1.13	61	53.7
Fe	800	1.03	63	51.7
Ff	674	0.89	47	49.9
Fg	675	0.87	46	49.5
Fh	671	0.87	46	49.7
Ha	628	0.8	49	50.6
Hb	558	0.71	32	48.9
Hc	554	0.71	32	48.8
Hd	663	0.95	42	53.1
He	566	0.96	35	50.5
Hf	668	1.05	47	52.9
Hh	572	0.79	NA	48.3

Figure 10. Whole dwelling average concentrations of pollutants: Optimised systems

The performance of the optimised systems are summarised in Figures 10 and 11. Note the assumed emission rate is much lower than in the initial modelling. It should be noted that the inclusion of 10000mm^2 air transfer grilles in internal doors, may not be acceptable, because of smoke movement, under fire regulations, which is why Approved Document F does not include them.

	VWA ug.m^{-3}	EVR l/s	EVR ach
Fb	38	39.3	1.31
Fc	65	23.2	0.77
Fd	62	24.4	0.81
Fe	63	23.9	0.8
Fh	47	32.1	1.07

Figure 11. Equivalent ventilation rates and volume weighted average concentration of formaldehyde for each ventilation system. Optimised systems. Average seasonal pollutant emission rate 1.5ug.s^{-1}

3. DISCUSSION

In studying the optimisation of the various ventilation systems, the basis of the research was to model the indoor air quality (IAQ) provided by systems that comply with the prescriptive guidance given in ADF (2006), when provided with typical internal pollutant emission scenarios. The pollutants were selected to represent certain characteristics of discharge e.g. unavoidable emissions arising from occupant activity and avoidable pollutants from building materials. The modelling produced 15-minute concentration time profiles of the pollutants of concern for a whole year of dwelling occupation. Not all ventilation strategies (and systems to exploit those strategies) provide the same level of IAQ when judged against typical indoor pollutant types. For example, pollutants that are emitted on a continuous basis are removed more effectively (in the long term) by continuous ventilation. Point source local emissions of pollutants can be better removed by local ventilation rather than continuous background ventilation.
Using the concept of ‘equivalent ventilation rate’ has allowed the development of optimised systems which provide approximately equivalent and acceptable IAQ. However, because of the underlying differences between operating methods of the systems they can not all be ‘optimised’ to give the identical spatial and temporal levels of IAQ. By using the ‘equivalent ventilation rate’ methodology, it was possible to suggest ‘maximum acceptable emission rates’ for avoidable pollutants. Interestingly, for formaldehyde this seems to be identical for the house and the flat were studied: for this pollutant and for the optimised systems considered, a maximum acceptable constant emission rate of 1.5 µg.m^{-3} seems to be appropriate for both dwelling types. If this condition is met, then the seasonal average formaldehyde concentration predictions are always less than the WHO recommended level of 100 µg.m^{-3} (30 minute exposure period), and many of them are actually less than 50 µgm^{-3}. Such an approach may have implications for pollutant emission standards, with systems optimised to meet certain levels of performance based on those standards.

ACKNOWLEDGEMENT

This research was funded by The Department of Local Government and Communities, Sustainable Buildings Division, Under the Building Operational Performance Framework contract: Ventilation Effectiveness BD 2523. The views expressed in this paper are however those of the authors.

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