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EMISSIONS FROM IRISH DOMESTIC FIREPLACES AND THEIR IMPACT ON INDOOR AIR QUALITY WHEN USED AS SUPPLEMENTARY HEATING SOURCE

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ABSTRACT

A field study on the impact of fireplace on the indoor air quality was carried out between 2004 and 2006, where two main contaminants, CO and particulate matters, were investigated in twenty seven randomly selected Irish houses. The results show that while the physical environment has been improved by increasing the room air and radiant temperature, indoor air quality is significantly decreased when fireplace is used as additional heating source to the central heating. The operation of fireplace increased transient concentrations of CO and airborne particle to several times higher than the normal house average level. Statistical analysis showed significant difference of the average PM10 concentration between house groups with and without using fireplace. However fireplace did not demonstrate a significant influence on average CO level from our samples. When comparisons were made between houses with various emission sources, i.e. fireplace, smoking and open fire gas cooking, and houses free of the above sources, smoking and open fire gas cookers were proved to be other major sources of particles and CO. Particularly when they exist at the same time with fireplace, significant elevation of CO and airborne particle levels is observed in analysis. Cumulative probability analysis in some houses revealed high percentage of time exceeding health guidelines which indicated the potential health risk in these houses. Mass balance equation was employed to estimate particle emission rates from fireplace, namely 0.66 mg min^{-1} (PM10) and 0.20 mg min^{-1} (PM2.5) respectively in terms of mass concentration. Emission rates on particle numbers were also estimated despite the relatively smaller sample. Gas fuel fireplaces tended to emit fewer particles both in mass and in number comparing to fireplaces using solid fuels.

KEYWORDS: fireplace, particulate matters, carbon monoxide, emission rate

1. INTRODUCTION

Fireplace is likely to retain a significant presence as an auxiliary heating source in Irish residences for both cultural and economic reasons. Many Irish one-family dwellings were heated totally or partially with traditional wood, coal or peat burning fireplace, particularly as Ireland is rich in peat resources. People use fireplace for its advantages in heating up individual rooms (mainly the living room), as top-up of centre heating and improving thermal comfort by increasing radiant temperature. But burning solid fuel is not only unsustainable (in the case of peat and coal), it also generates a wide spectrum of particulate and gaseous air pollutants such as respirable particles (PM10) and non-respirable particles, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), and polycyclic aromatic hydrocarbons

(PAH). Many authors reported the influence of wood-burning appliance to both the home and the ambient air quality from investigation studies around the world (Gilbert *et al.,* 2006; Glasius *et al.,* 2006; Levesque *et al.,* 2001). Some other studies, e.g. Menghini *et al.* (2007), attempt to reduce the environmental impact of open fireplaces. But in Ireland very little attention has been paid so far to the domestic air pollution induced by open fireplaces. Our purpose of this study is to find out the pollutant emissions (particulate matters and CO) from traditional open fire devices.

2. METHODOLOGY

In total twenty seven randomly selected sing-family houses were available from a parallel study for the investigation. Indoor air contaminants including particulate matters and CO were continuously monitored in these houses. The features of each house are summarized in table 1. All 27 houses are equipped with at least one fireplace, in the living room; with some older houses containing extra fireplaces in other habitable rooms. For example, house BGP (built in 1874) has a fireplace in the study room locating between the first and second floor. House SDF (built in 1935) and SKA (built in 1867) still keep the original fireplaces in every habitant room, although only the one in the living room is in use. It is to be noted that we did not include samples with fireplaces having direct combustion air supply, which is increasingly in new dwellings. Presumably all gas pipes were flued – apparently common in some apartments to find "decorative" flueless gas fires. Information on throat restrictors in the flue which reduce ventilation rate when not in use is also not included in the discussion. Fireplaces in 16 houses are regularly operated during the winter, 12 of them had been operated during the test period with recorded schedules. Those in the rest 11 houses are rarely/never used and some of them have been blocked. There were no obvious correlations found between the household characteristics and their usage of the fireplaces. However lower income families (living in social houses) tend to operate their fireplace for longer time. Peat baguette, wood or coal is the main burning fuel, except house SDF and SKA have retrofitted to gas fires. To distinguish from other combustion emissions, information on other sources related to indoor CO and particle emission (such as cooking and smoking) is also included in table 1. A questionnaire on dwelling characteristics and occupant lifestyles, e.g. the use of heating, windows, ventilation, and the presence of animals, chemicals etc, was completed by the occupants. Occupants were requested to record the time and duration of fireplace usage in the log sheet which was distributed at the beginning of the measurement. Activities such as cleaning (vacuum), extra guests, smoking and opening windows/doors were also recorded.

For each house, continuous monitoring of carbon monoxide, airborne particles and hygro-thermal environmental conditions was carried out for a period of 2 to 7 days. The objective was to obtain the temporal variation in concentration of the selected contaminants during normal occupancy over a typical period. Mass concentration of PM2.5 and PM10 were measured using a portable light scatter particle counter (Model: MetOne AEROCET 531). Number concentration of particles in the size range of 0.5 μm to 5 μm was measured by the same equipment. Ultrafine particle (smaller than 1 micrometer in aerodynamic diameter) numbers in house SKA and WFB were measured using a portable condensation nucleus counter TSI P-Trak 8525 from a parallel study (McLaughlin and Hogg, 2006). The equipment was programmed to sample the air for 2 minutes every 15 minutes. CO concentrations were measured using HOBO monoxide logger, which was operated by an electrochemical cell consisting of electrodes in an acid electrolyte. The measuring range was from 0 to 125ppm, giving a reading with an accuracy of ±5% of the instantaneous concentration. In order to estimate the particle emission rates from household fireplaces according to the mass balance equation, which is described in section 3.3, the whole house air exchange rates were measured by using SF_6 tracer gas decay method (Guo *et al.,* 2005).

Table 1. Brief summary of sampled house features

House	Age	Type*	Area	Main heating**	Main cooking	Use of Fireplace	Fuel for Fireplace	Indoor smoking
AVB	2004	D	Rural	Oil CH/Elec. UF	Elec.	Yes	Peat	No
BGP	1874	SD	Urban	Gas CH	Gas/Elec.	Yes	Peat	No
BGS	1870	D	Urban	Gas CH	Gas	No	N/A	No
BRY	2004	CT	Suburb	Gas CH	Gas	No	N/A	No
CHT	1928	CT	Urban	Gas CH	Elec.	No	N/A	No
DUF	1898	CT	Urban	Gas CH	Gas	No	N/A	No
ENF	2004	SD	Rural	Gas CH	Elec.	No	N/A	No
FHP	1960	CT	Suburb	Gas CH	Elec.	Yes	Wood	No
LDT	2002	CT	Urban	Gas CH	Elec.	No	N/A	Yes
MPA	1992	D	Suburb	Gas CH	Elec.	No	N/A	No
MPB	1992	D	Suburb	Gas CH	Gas	No	N/A	No
MPC	1992	CT	Suburb	Gas CH	Elec.	No	N/A	No
MWA	2003	CT	Urban	Gas CH	Elec	No	N/A	Yes
MWB	2003	CT	Urban	Gas CH	Gas/Elec	No	N/A	Yes
MWC	2003	ET	Urban	Gas CH	Elec	Yes	Wood/coal	Yes
MWD	2004	ET	Urban	Gas CH	Elec	Yes	Peat/coal	No
OBR	1930	ET	Urban	Elec. IH	Bottle gas	No	N/A	No
OCP	2003	CT	Urban	Gas CH	Elec	Yes	Wood/coal/peat	Yes
SDF	1935	D	Urban	Gas CH	Gas	Yes	Gas	No
SKA	1867	CT	Urban	Gas CH	Elec.	Yes	Gas	No
SKB	1867	CT	Urban	Gas CH	Gas	Yes	Peat/coal	No
WAA	2002	CT	Urban	Gas CH	Elec	No	N/A	No
WAB	2002	CT	Urban	Gas CH	Elec	No	N/A	Yes
WAC	2002	CT	Urban	Gas CH	Elec	Yes	Wood/coal	No
WFA	1981	SD	Suburb	Oil CH	Elec.	Yes	Peat	No
WFB	1981	D	Suburb	Oil CH	Elec.	Yes	Peat/coal	No
WHW	2003	D	Urban	Gas CH	Elec	No	N/A	Yes

* House type: D – Detached; SD – Semi-detached; CT – Centre-terrace; ET – End-terraced.
** CH – Centre heating; IH – Individual heaters; UF – Under-floor heating; Elec. – Electricity.

3. RESULTS AND DISCUSSIONS

3.1 Effect of fireplace on increasing transient contaminant levels

In plotting the concentration of measured particle and CO, specific patterns for each house can be observed in terms of emission, accumulation, peak level and decay rate etc reflecting household activities. And sometimes the patterns are distinguishing for weekdays and weekends). Using the schedule which recorded the times during which fireplace was in use, we can determine the contribution of the fireplace to increased indoor CO and PM10 levels. Figure 1 and figure 2 show two examples. In house AVB, the peak levels of PM10 (0.167 mg m^{-3}) and PM2.5 (0.155 mg m^{-3}) coincide with the fireplace being in use between 18:00 and 24:00 on 8th Feb. The levels are about 4 (PM10) and 9 (PM2.5) times higher than during normal occupancy conditions without using fireplace on 9th and 10th Feb. The second peak level of PM10 (0.124 mg m^{-3}) represented the influence from a normal full house cleaning, which is obviously different from burning fire since it mainly caused the re-suspension of larger size particles. The peak level of total suspended particles (not shown in figure 1) is as high as 0.243 mg m^{-3} in this occasion. Figure 2 shows a significant increase of CO concentration indicated the impact of gas fire in another house sample.

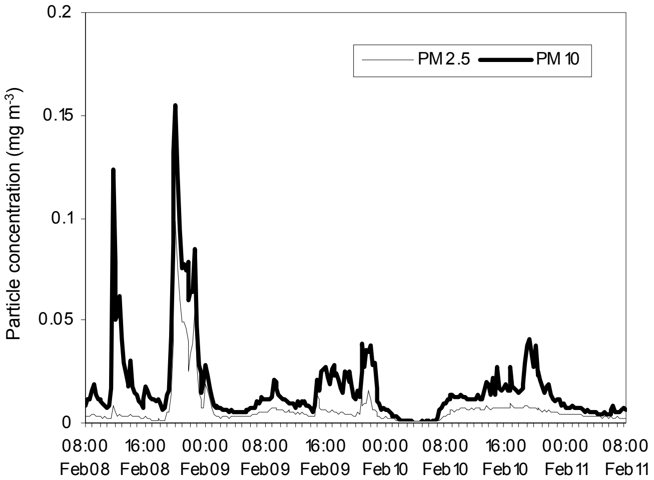

Figure 1. Time-scale variation of particle Concentrations in house AVB

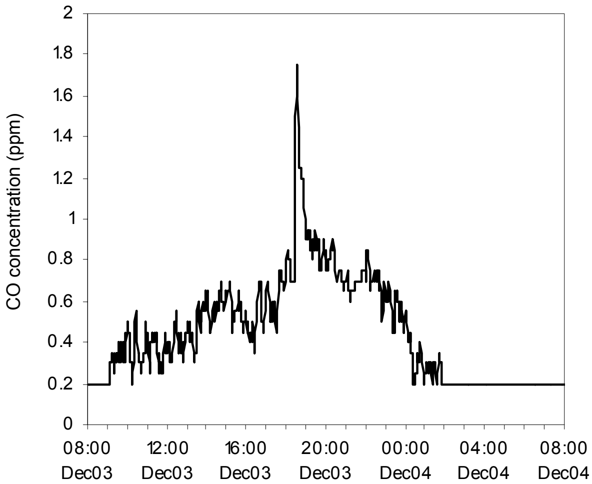

Figure 2. Time-scale variation of CO concentrations in house SDF

3.2 Comparison of houses with various pollutant sources

Table 2 summarized the average value of PM10 and CO concentration over each test period in the 26 houses investigated. (Unexpected construction work was done during the sampling period of house MWB, which caused unusual particle concentrations; so the results were excluded from the summary). To eliminate the confusion caused by other indoor sources of CO and particles, houses with identical sources were grouped to make comparisons. The other sources we considered in this study besides fireplace are smoking and open fire gas cookers. Table 3 showed the average concentrations in houses with these identified indoor sources. Regarding PM10, all three sources showed positive impact although smoking seemed to play strongest influence. As to CO, both smoking and gas fuel showed distinguishing effect. So it is not surprising that houses with both solid fuel burning fire and gas cooking had the highest average CO level among our samples. Statistical analyses were performed to compare means between groups with specific pollutant sources and that free of these sources using the one-sided Student's t – test (the confident level $\alpha=0.05$). Results showed significant impact from the fireplace, smoking, open fire gas cooking and the combination of these sources, on the average indoor PM10 and CO concentration, except that the effect of fireplaces on the CO concentration cannot be statistically proved according to our samples.

Considering the influence from outdoor air pollution, an accumulative frequency plot (figure 3) was employed to show the particle concentrations distribution of nine houses from the same area so that we can assume that they are in the same ambient air conditions. Other similarities among these houses include house age (all were built between 2003 and 2004), social background (all social houses) and management (all under the same construction inspector and managed by the same company). On the one hand, results showed distinctive profile of PM10 accumulative frequency in each house and two main resources of particles, which are combustion fireplace and smoking, could be identified again. On the other hand, the profiles illustrated the generally poor air quality in the investigated households with 20 to 30% of time exceeding the threshold level of PM10 exposure (50 μg m^{-3}) in most houses (7/9), and this figure approached 70% in the worst case (house OCP). The possibly multi factors which led to the existing condition should cause our attention.

3.3 Estimation of particle emission rates from open fire

The principle factors governing the levels of airborne particles indoors are the contributions from indoor and outdoor sources, the deposition rate of particles on indoor surfaces, and the ventilation rate. Then a mass balance formula can be employed to calculate indoor particle concentration taking into account of the above factors as shown below.

Table 2. Summary of PM10 and CO concentrations in tested houses with identified indoor pollutant sources

Pollutant sources *	F	S	G	FS	FG	N
			PM10			
PM10 concentration (mg m^{-3})	0.016	0.102	0.026	0.083	0.024	0.01
	0.026	0.045	0.019	0.095	0.072	0.013
	0.036	0.04	0.046			0.002
	0.028	0.054	0.015			0.015
	0.012		0.028			0.026
	0.024		0.015			
			0.011			
Average	0.024	0.060	0.023	0.089	0.048	0.013
			CO			
CO concentration (ppm)	0.53	0.56	0.95	-	0.9	0.22
	0.2	-	0.59	-	1.63	0.47
	0.27	1.05	1.71			-
	1.5	1.23	1.29			0.62
	0.31		0.57			0.32
	0.44		0.91			
			0.33			
Average	0.54	0.95	0.91		1.27	0.41

* Identified pollutant sources: F – Fireplace; S – Smoking; G – Open fire gas fuel cooking; FS – Fireplace and Smoking; FG – Fireplace and open fire gas cooking; N – None of the above.

Table 3. p-value of the Student's t-test between different groups of houses (α=0.05)

groups / Pollutant	F vs. N	S vs. N	G vs. N	FS vs. N	FG vs. N
PM10	0.020	0.010	0.034	0.002	0.015
CO	0.087	0.004	0.002	-	0.002

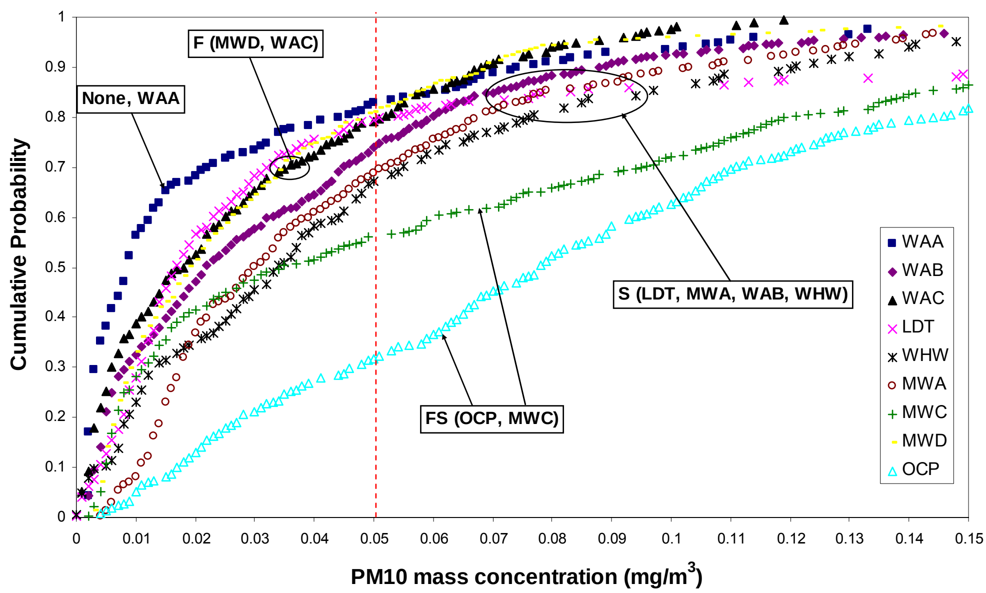

Figure 3. Cumulative probability distribution of PM10 concentration in 9 selected houses

$$\frac{dC_{in}}{dt} = P\alpha C_{out} + \frac{Q_s}{V} - (\alpha + \kappa)C_{in} \tag{1}$$

where: C_{in}/C_{out} – indoor/outdoor particle concentration
P – penetration efficiency
α – air exchange rate
k – deposition rate
Q_s – indoor particle generation rate
t – time
V – efficient volume of the house (assume homogenous concentration inside house)

Previous studies discussed the use of this equation for determination of source emissions and prediction of indoor air pollutant concentration levels (He *et al.* 2005; He *et al.* 2004). Some assumptions have been made to simplify the equation. For example, the penetration efficiency (*P*) is assumed to be one for both coarse and fine particles; outdoor particle concentration is assumed to be the initial indoor particle concentration when no indoor source is in operation. Average values of air exchange rate, particle deposition rate are used in order to get a further simplified equation (2), which enables us to calculate the particle emission rate from burning fireplace.

$$\overline{Q_s} = V \times \left[\frac{C_{\text{int}} - C_{in0}}{\Delta T} + \overline{(\alpha + \kappa)} \times \overline{C_{in}} - \overline{\alpha} \times C_{in0} \right] \tag{2}$$

where: $\overline{Q_s}$ - average emission rate (mg min^{-1} or Pt min^{-1});
$C_{\text{int}}/C_{\text{in0}}$ – peak/initial indoor particle concentrations (mg m^{-3} or Pt m^{-3});
$\overline{\alpha}$ – average air exchange rate (min^{-1});
$\overline{(\alpha + \kappa)}$ – average total removal rate (min^{-1});
ΔT – time difference between initial and peak concentration (min);

Equation (2) can be used for calculations of both particle mass and number concentrations and emissions, although it has most commonly been used for mass balance. We used it to determine indoor source particle emission rate (mass and number) of fireplace in the 3 houses with analyzing particles time series concentration data and occupants' self-recorded activity log. In the calculation, we also made the following assumptions: particles distribute homogenously within the house space; the fireplace is the only source of particles during the calculated occasion.

The average mass emission rates of PM2.5, PM10 and particle number emission and size distribution (submicron particles, particles >0.5 u and particles >5 u) from domestic fireplaces are given in table 4. The results have shown high degree of consistency with similar study by He *et al.* (He *et al.* 2004) in terms of PM2.5 mass emission rate and submicron particle emission rate from stove in their study. Variety influence from burning appliance, chimney/ventilation performance, burning fuels etc. can also be observed from different occasions listed in the results. For example, gas burning fireplaces (in SDF and SKA) tend to emit much fewer particles both in mass and in number comparing to fireplaces using solid fuels. Other influences include type of solid fuels, firing duration, household habits, and chimney/ventilation performance. The vast number of submicron particles emitted from the fireplace and their health effect on the occupants should be carefully considered.

4. CONCLUSION

While the physical environment has been improved by increasing the room air and radiant temperature, indoor air quality is significantly decreased when fireplace is used as additional heating source to the central heating. The operation of fireplace increased transient concentrations of CO and airborne particle to several times higher than the normal house average level. Statistical analysis showed significant difference of the average PM10 concentration between house groups with and without using fireplace. However fireplace did not demonstrate a significant influence on average CO level from our samples.

Table 4. calculation results of particle emission rates

House code	Volume (m^3)	Calculate occasions	PM10 mass concentration and emission			PM2.5 mass concentration and emission		
			Peak (mg m^{-3})	Ratio	Emission rate (mg min^{-1})	Peak (mg m^{-3})	Ratio	Emission rate (mg min^{-1})
AVB	525	1	0.155	25.8	0.94	0.098	98.0	0.60
		2	0.131	11.9	2.70	0.034	5.7	0.46
		3	0.036	2.4	0.54	0.016	4.0	0.50
FHP	213	1	0.073	5.6	1.06	0.038	7.6	0.59
		2	0.091	7.6	0.38	0.032	5.3	0.13
		3	0.095	4.1	0.64	0.027	3.4	0.15
		4	0.083	10.4	0.66	0.048	24.0	0.37
MWD	225	1	0.078	1.7	0.23	0.05	3.8	0.19
		2	0.129	9.9	0.40	0.028	9.3	0.09
WFB	300	1	0.057	28.5	0.84	0.007	-	0.10
		2	0.018	3.6	0.15	0.003	3.0	0.02
		3	0.066	16.5	0.64	0.007	-	0.06
		4	0.054	54.0	0.57	0.004	-	0.04
		5	0.051	8.5	1.15	0.003	-	0.08
SDF	280	1	0.015	1.7	0.12	0.004	1.3	0.02
SKA	238	1	0.007	1.8	0.07	0.002	2.0	0.02
		2	0.025	1.7	0.07	0.006	1.2	0.02
Mean					**0.66**			**0.20**
SD					**0.63**			**0.21**

House code	Volume (m^3)	Calculate occasions	Particle (>0.5 u) number concentration and emission			Particle (>5 u) number concentration and emission		
			Peak (Pt cm^{-3})	Ratio	Emission rate (Pt min^{-1} $\times 10^8$)	Peak (Pt cm^{-3})	Ratio	Emission rate (Pt min^{-1} $\times 10^6$)
FHP	213	1	58.30	14.1	5.49	126	63.0	1.36
		2	61.40	2.1	8.22	232	3.7	5.03
		3	43.93	7.4	8.81	217	9.4	5.28
		4	48.56	2.8	3.53	379	6.2	4.17
		5	108.81	20.5	3.67	373	4.0	4.30

House code	Volume (m^3)	Calculate occasions	Submicron particles					
			Peak (Pt cm^{-3})	Ratio	Emission rate (Pt min^{-1} $\times 10^{11}$)			
WFB	300	1	43600	8.0	5.98	-	-	-
SKA	238	1	6265	1.2	0.04	-	-	-

When comparisons were made between houses with various emission sources, i.e. fireplace, smoking and open fire gas cooking, and houses free of the above sources, smoking and open fire gas cookers were proved to be other major sources of particles and CO. Particularly when they exist at the same time with fireplace, significant elevation of CO and airborne particle levels is observed in analysis. Cumulative probability analysis in some houses revealed high percentage of time exceeding health guidelines which indicated the potential health risk in these houses. Mass balance equation was employed to estimate particle emission rates from fireplace, namely 0.66 mg min^{-1} (PM10) and 0.20 mg min^{-1} (PM2.5) respectively in terms of mass concentration. Emission rates on particle numbers were also estimated despite the relatively smaller sample. Gas fuel fireplaces tended to emit fewer particles both in mass and in number comparing to fireplaces using solid fuels. The vast number of fine particles (between 0.5 u and 5 u) and submicron particles generated from the fireplace and their health effect on the occupants should be carefully considered.

However, contribution from other influences such as type of solid fuels, firing duration, household habit, or chimney/ventilation performance need further discussion. Poor indoor air quality in some extreme cases should be put more attention. Relationship between contaminant level and energy sources, assessment of potential health risk will be included in the future investigation.

REFERENCES

Gilbert N.L., Gauvin D., Guay M., Heroux M-E., Dupuis G., Legris M., Chan C.C., Dietz R. N. and Levesque B. (2006) Housing characteristics and indoor concentrations of nitrogen dioxide and formaldehyde in Quebec City, Canada, *Environmental Research*, **102**(1), 1-8.

Glasius M., Ketzel M., Wahlin P., Jensen B., Monster J., Berkowicz R. and Palmgren F. (2006). Impact of wood combustion on particle levels in a residential area in Denmark, *Atmospheric Environment*, **40**(37), 7115-7124.

Guo L., Lewis J.O., Kelly A. and Lennon D. (2005) Field investigation of indoor air quality and ventilation characters in selected Irish houses, In: *The 10th International Conference of Indoor Air Quality and Climate - Indoor Air 2005*, Beijing, China.

He C., Morawska L. and Gilbert D. (2005) Particle deposition rates in residential houses, *Atmospheric Environment*, **39**(21), 3891-3899.

He C., Morawska L., Hitchins J. and Gilbert D. (2004) Contribution from indoor sources to particle number and mass concentrations in residential houses, *Atmospheric Environment*, **38**(21), 3405-3415.

Levesque B., Allaire S., Gauvin D., Koutrakis P., Gingras S., Rhainds M., Prud'Homme H. and Duchesne J-F. (2001) Wood-burning appliances and indoor air quality, *The Science of the Total Environment*, **281**(1-3), 47-62.

McLaughlin J. and Hogg C. (2006) The influence of ultrafine particles and occupancy factors on the risk from radon in some Irish Dwellings, In: *Healthy Buildings 2006*, Lisbon, Portugal.

Menghini D., Marchione T., Martino G., Marra F.S., Allouis C. and Beretta F. (2007) Numerical and experimental investigations to lower environmental impact of an open fireplace, *Experimental Thermal and Fluid Science*, **31**(5), 477-482.