INDOOR RADON CONCENTRATION IN A TEST CHAMBER: EXPERIMENTAL DATA AND THEORETICAL EVALUATIONS

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ABSTRACT

This paper reviews the preliminary work performed to evaluate the influence of building materials on Radon concentration. Experiments were carried out under various conditions in order to examine data variability in a test chamber built in Milan. A mathematical model, based on the Jacobi-Pörstendorfer theory, was developed to predict Radon and daughters concentrations in the chamber. The model yields Radon concentration estimates that agree with experimental data and permits Radon progeny concentrations and doses in the chamber to be evaluated.

INTRODUCTION

The Italian National Electricity Board (ENEL) has set up, in cooperation with CISE, an investigation program for the purpose of assessing the hazards connected with coal ashes being used as partial substitutes for cement and other building materials in civil applications. This program refers specifically to Radon emanation characteristics, since Radon is the major natural radiological hazard for the community. Preliminary laboratory tests on the exhalation rate of powdered samples had shown a slight contribution of fly ashes to indoor Radon concentrations(1). In order to confirm these evaluations, two identical rooms (3.4 x 3.8 x 2.15 m) were built using conventional and fly ash-containing building materials. The two rooms were separated from the ground by a 40 cm high crawl-space. A sandy underlying soil with a high porosity level and sidewise diffusion and a shallow foundation were used to obtain the lowest possible Radon concentration in the crawl-space in order to enhance the Radon emanation of the rooms' building materials.

The principal objectives of this work were to develop a mathematical model for estimating Radon levels in a test chamber, and to verify the accuracy of the model output by a comparison with experimental data.

METHODS

The study site was a test chamber, located near Milan, made of conventional building materials. Facilities were provided to produce any desired temperature, humidity and air-change conditions within the room. The following parameters were continuously monitored: Radon concentration inside the room, in the open air and in the crawl space; meteorological parameters (outdoor and indoor temperatures, differential atmospheric pressure, humidity). The air change rate was controlled by an SF_6 measurement system (see Appendix).

Experimental conditions were continuously changed, during the period November 1990 - August 1991, to evaluate the influence of various parameters (air-conditioning system, ventilation, humidity, differential pressure, differential temperature, Radon levels in the crawl space) on indoor Radon concentration. Mean values for all parameters are given in Table 1.

In order to evaluate the indoor Radon concentration which is not related to that outside by ventilation, hourly Radon entry rates were determined by using a general mass balance equation:

$$\frac{dC^{INDOOR}}{dt}=E_S\frac{S}{V}+\lambda_V C^{OUTDOOR}-(\lambda_V+\lambda_{Rn})\,C^{INDOOR} \quad (1)$$

where C^{INDOOR} = indoor Radon concentration [Bq m^{-3}], $C^{OUTDOOR}$ = outdoor Radon concentration [Bq m^{-3}], E_s = Radon exhalation rate from walls [Bq m^{-2} h^{-1}], S = room surface area [m^2], V = room volume [m^3], λ_v = ventilation rate [h^{-1}], λ_{Rn} = Radon decay constant [h^{-1}]. Assuming $\beta=E_sS/V+\lambda_vC^{OUTDOOR}$ and $\alpha=\lambda_v+\lambda_{Rn}$, the general solution of this equation, over a particular time step $\Delta t=t-t_0$, is:

$$C^{INDOOR}(t)=\frac{\beta}{\alpha}[1-\exp(-\alpha\Delta t)]+C^{INDOOR}(t_0)\exp(-\alpha\Delta t) \quad (2)$$

Using measurement data to supply hourly values of indoor Radon concentration and air change rates, Effective Radon Entry Rates (ERER=[Bq m^{-3} h^{-1}]) were calculated for each hour of the period using the following relation(2):

$$ERER(t)=\alpha\left[\frac{C^{INDOOR}_{measured}(t)-(C^{INDOOR}_{measured}(t_0)\exp(-\alpha\Delta t))}{1-\exp(-\alpha\Delta t)}\right]-\beta \quad (3)$$

Seasonal averages of the measured and calculated parameters are shown in Table 2 (the ventilation rate is derived using mass balance formula in Appendix and ERER is calculated considering that Radon exhalation rate from walls is quite constant with an average value of about 2 Bq m^{-2} h^{-1}).

In order to predict Radon and daughters concentrations in the chamber, a general mass balance model was developed. This model, called RADBOX, represents a dynamic version of Jacobi-Pörstendorfer one and it is stated as a system of differential equations reflecting the mass balance among Radon (equation 1) and its progeny in the three forms: free, attached and deposited(3)(4)(5).

Using available data for attachment, deposition and desorption rate constants, it is possible to estimate Radon and its progeny concentrations, equilibrium factor and Potential Alpha Energy Concentration (PAEC) inside the chamber.

RESULTS AND DISCUSSION

As shown in Table 1 and 2, measurements carried out inside the test chamber indicate the dependence of Radon concentration with ventilation and stack effect (variation of differential pressure with height across a vertical wall separating air masses of different temperatures). An increase in ventilation causes a diminution of the differential pressure ($P_{outdoor}-P_{indoor}$), due to the inlet of outdoor air. Both the lower Radon concentration in the outdoor air and the suppression of the upward airflow from the crawl-space (more contaminated) determine a lowering of indoor Radon concentrations (see Table 1 experimental conditions 2, 3 and 8). From Table 2, seasonal variations of indoor Radon concentrations and Radon entry rates (ERER) are related to stack effect action on upward airflow in the chamber. Higher Radon concentrations (40-50 Bq m^{-3}) and higher entry rates (5-7 Bq m^{-3} h^{-1}) in autumn and winter were consistent with lower differential temperature ($T_{outdoor}$ - T_{indoor}) and higher differential pressure (about to 1.8 Pa). During spring and summer both the differential temperature and differential pressure were mostly close to zero. This means that the stack effect was suppressed and Radon entry rates were low. The aspiration of air from the crawl space (see table 1 experimental condition 16) does not show a great influence on the indoor Radon levels because of the low residual Radon concentration in the crawl-space.

A comparison of model results with observations shows that hourly average predictions for indoor Radon concentrations (>10 Bq m^{-3}) are within 14 % agreement of the corresponding experimental data. Calculated and observed hourly ^{222}Rn concentrations for two different ventilation conditions (λ_v = 2.1 and 0.69 h^{-1}) are compared in Figs 1 and 2 respectively. Calculated values for ^{222}Rn are in close agreement with observations, but a model-observation discrepancy occurs for low values (3÷10 Bq/m^3).

APPENDIX: TWO WAYS TO ESTIMATE VENTILATION IN THE TEST CHAMBER

Since ventilation measurements using SF_6 techniques are only possible in some representative situations, two different approaches are being used for continuous ventilation monitoring.

The first one estimates ventilation using a power law expression $\lambda_v = VD\Delta P^n$ where D=permeability of building envelope [h^{-1} Pa^{-n}], ΔP = pressure drop across the building envelope [Pa] and n=flow exponent [dimensionless]. In this study we used n=0.65[6] and a value of D=0.76 h^{-1} $Pa^{-.65}$, calculated according to previous formula, when both ventilation rate and pressure drop were available.

The second approach is derived from the mass balance equation (1) assuming steady state conditions and neglecting λ_{Rn}; so that λ_v can be evaluated from measurements of Radon emanation and indoor and outdoor Radon concentrations using this formula:
$\lambda_v = (E_0 S/V)/(C^{INDOOR} - C^{OUTDOOR})$

Figure shows the comparison between measured (SF_6 technique) and calculated ventilation rates (Power law and mass balance formula)

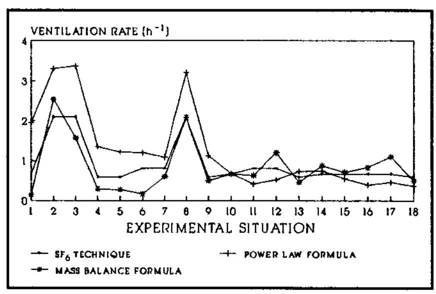

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Table 1: Experimental conditions inside the test chamber in the period: November 1990 - August 1991

Experimental condition	Inlet air from outdoor	Outlet air toward outdoor	Ventilator	Umidifier	Period	Radon concentrations indoor [Bq m^{-3}]	Radon concentrations outdoor [Bq m^{-3}]	Radon concentrations crawl-space [Bq m^{-3}]	Tout-Tin [°C]	Pout-Pin [Pa]	Humidity [%]	Ventilation [h^{-1}]
1	OPEN	OPEN	OFF	OFF	11/09-11/23	47.5	30.9	---	-13.5	1.8	43.6	0.7
2	OPEN	OPEN	ON	OFF	11/23-12/05	21.1	20.8	---	-15.7	-9.6	27.8	2.1
3	CLOSED	CLOSED	ON	OFF	12/05-01/07	29.9	27.4	191.8	-17.6	-9.9	24.5	2.1
4	CLOSED	CLOSED	OFF	OFF	01/07-01/10	44.2	29.6	254.2	-15.7	1.9	33.6	0.6
5	CLOSED	CLOSED	OFF	ON	01/10-01/22	39.3	25.8	257.5	-15.4	2.1	47.9	0.6
6	CLOSED	OPEN	OFF	ON	01/22-01/31	57.1	36.7	120.0	-13.6	2.0	54.2	0.8
7	OPEN	CLOSED	OFF	ON	01/31-02/07	32.2	21.0	253.9	-14.2	1.8	49.5	0.8
8	OPEN	CLOSED	ON	OFF	02/07-03/12	24.5	24.9	153.3	-12.1	-9.2	36.0	2.1
9	CLOSED	CLOSED	OFF	OFF	03/12-03/14	29.0	20.6	231.6	-6.2	0.8	62.5	0.6
10	OPEN	OPEN	OFF	OFF	03/14-03/22	30.4	24.9	266.8	-5.8	0.9	59.7	0.7
11	CLOSED	OPEN	OFF	OFF	03/22-03/25	22.3	17.3	297.9	-7.6	0.1	71.8	0.8
12	OPEN	CLOSED	OFF	OFF	03/25-04/09	20.3	16.5	181.1	-5.4	0.2	58.6	0.8
13	CLOSED	CLOSED	OFF	OFF	04/09-05/03	24.4	15.9	215.2	-5.9	-0.1	58.4	0.6
14	OPEN	OPEN	OFF	OFF	05/03-06/14	18.0	13.6	190.8	-3.0	0.5	48.8	0.7
15*	OPEN	OPEN	OFF	OFF	06/14-08/05	21.3	17.1	181.8	5.0	0.2	51.2	0.7
16*,**	OPEN	OPEN	OFF	OFF	08/05-08/08	29.0	24.1	43.9	8.2	-0.1	48.2	0.7
17*	OPEN	OPEN	OFF	OFF	08/08-08/19	22.8	19.2	204.4	6.3	0.2	51.9	0.7
18*	CLOSED	CLOSED	OFF	OFF	08/19-08/22	26.2	19.7	273.1	5.3	0.3	57.7	0.6

* = Conditioning system set in refreshing air position
**= Air aspiration from crawl-space

Table 2: Seasonal variation of measured and calculated parameters inside the test chamber with air change rate in the range 0.6÷0.8 h^{-1}

Season	Radon concentrations indoor [Bq m^{-3}]	Radon concentrations outdoor [Bq m^{-3}]	Radon concentrations crawl-space [Bq m^{-3}]	Tout-Tin [°C]	Pout-Pin [Pa]	ERER [Bq m^{-3} h^{-1}]	Ventilation* [h^{-1}]
Autumn ('90)	47.5	30.9	---	-13.5	1.8	5.6	0.1
Winter (90/91)	40.5	27.2	226.2	-13.0	1.8	7.7	0.4
Spring ('91)	20.4	15.0	196.8	-3.9	0.3	2.0	0.8
Summer ('91)	23.2	18.6	189.1	5.6	0.1	1.3	0.8

* = Ventilation calculated using reduced mass balance formula in Appendix

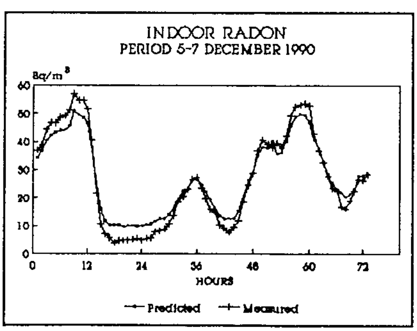

Figure 1: Application of RADBOX model to the test chamber (ventilation = 2.1 ACH)

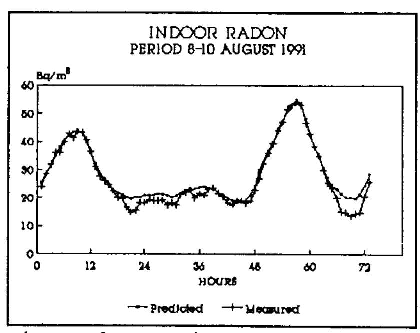

Figure 2: Application of RADBOX model to the test chamber (ventilation = 0.67 ACH)