INFILTRATION AND AIR QUALITY IN WELL-INSULATED HOMES: 3. MEASUREMENT AND MODELING OF POLLUTANT LEVELS

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Abstract

Indoor pollutant levels in well-insulated houses are being investigated in a 2-year theoretical and experimental study involving the simultaneous measurement of meteorological variables, air exchange and circulation, and energy consumption. This paper describes concentrations of radon, radon progeny, formaldehyde, carbon monoxide, and nitrogen oxides observed in two houses over two seasons, summer and fall 1983. Two companion papers provide a perspective on the problem and the study design, and present results of energy use and infiltration measurements.

Experimental Setup

In this project sponsored by the Electric Power Research Institute, pollutant levels inside and outside two identically constructed houses have been monitored during the summer and fall of 1983. The monitoring is continuing through the 1983-84 winter season. One of these bilevel houses, termed the experimental house, was retrofitted to reduce its air leakage rate by 40 percent, as measured by the fan pressurization/depressurization method, and was equipped with an air-to-air heat exchanger. The other house was left in its initial state of construction to serve as a control.

Levels of carbon monoxide (CO), nitrogen dioxide (NO_2), radon, and radon progeny are monitored continuously in the upstairs and downstairs zones of each house as well as outdoors. The monitoring data are summarized as 15-minute averages by an onsite data logging system. Inhalable particulate (IP) and formaldehyde (HCHO) levels are measured with integrated samples over minimum collection periods of 24 hours.

Weekly experiments have been defined in terms of the circulation fan setting for both houses and the heat exchanger flow rate for the experimental house (1). The circulation fan is part of a central forced-air system for heating and air conditioning. This fan is either kept off constantly, kept on constantly, or allowed to operate when heating or air conditioning is demanded. With this latter setting, which represents the customary mode of operation in U.S. households, the heat exchanger is either turned off, operated at its maximum flow rate, or operated at one of two intermediate flow rates termed low and medium. This paper reports the effects of selected fan and heat exchanger settings on indoor pollutant levels, based mainly on data collected during the summer of 1983.

Carbon Monoxide and Nitrogen Dioxide

Table 1 shows the effect of the heat exchanger and range exhaust fan on upstairs CO concentrations following use of the gas range. Both peak and 8-hour average concentrations are reported in the table. The range fan was operated only while the range was used, whereas the heat exchanger was operated continuously. Although both initial indoor concentrations and average outdoor concentrations were quite low, their respective effects on peak and average concentrations were removed with the aid of mass balance modeling.

Table 1. Effect of heat exchanger and range exhaust fan on upstairs CO concentrations following gas ignition.*

	Peak concentration, ppm		8-hour average, ppm	
	Control house	Experimental house**	Control house	Experimental house**
Range fan off	5.2	6.0	2.8	1.1
Range fan on	2.5	2.4	1.2	0.4

* One burner operated at maximum and the oven operated at 175° C (350° F) for a period of 40 minutes.

** Heat exchanger operated continuously at the maximum flow rate.

The figures in Table 1 indicate that the range exhaust fan reduced peak concentrations by over 50 percent in both houses, but the heat exchanger did not reduce the peak concentration. The heat exchanger reduced the 8-hour average concentration by over 60 percent, and the range fan achieved nearly the same reduction. Combined use of the heat exchanger and range fan reduced peak concentrations by over 60 percent and average concentrations by more than 80 percent.

In Figure 1, concentrations associated with gas range operation are shown for four upstairs locations, one downstairs location, and a location between the two floors. The circulation fan, range exhaust fan, and heat exchanger were not used during this particular period. The gas range was operated for a period of 40 minutes, starting at approximately 1515. Within one hour after the range was turned on, all locations on the upper floor had similar concentrations, but as reflected by the monitoring sites at the intermediate and lower levels, elevated CO concentrations were essentially confined to the upper level. Thus, although the mixing of contaminants in the horizontal direction was excellent, vertical mixing was seriously hampered, most likely as a result of thermal stratification.

Indoor concentrations of NO_2 increased when the gas range was operated but decayed quite rapidly. Mass balance modeling was used to estimate the rate constant for NO_2, assuming a first order reaction. Estimated reaction rates varied from 1.9 to 3.4, with an average of 2.6 ± 0.2. For each occasion of range use, the rate constant estimates decreased over time, indicating that the reaction is of a higher order. The nature of the decay reaction is being further investigated.

Formaldehyde and Particulates

In both houses, HCHO levels were always higher upstairs than downstairs; this result was expected because the predominant sources were pieces of furniture located upstairs. The ratio of upstairs to downstairs levels decreased in both houses as the extent of circulation fan activity increased. In Figure 2, the effect of the heat exchanger on HCHO levels is shown. For this figure, the upstairs and downstairs concentrations of HCHO were weighted by their respective fractions of the total house volume to derive summary concentrations for each house. The figure shows the ratio of experimental to control house concentrations for various heat exchanger settings. When the heat exchanger was off, levels were 10-15 percent higher in the experimental house. The ratio decreased as the heat exchanger flow rate increased; at the maximum flow rate, levels were about 30 percent lower in the experimental house.

IP levels at the study site were quite low in all monitoring zones but were always lower indoors than outdoors. Indoor-to-outdoor ratios were lowest when the circulation fan was operated constantly and highest when the heat exchanger was operated at the maximum flow rate. Thus, increased air circulation tended to lower indoor levels, whereas increased air exchange tended to raise indoor levels.

Radon

Radon gas concentrations and radon progeny working levels were measured with independent monitoring devices. The effects of the heat exchanger and circulation fan on radon levels in the experimental house are summarized in Table 2. For the first case presented in the table, neither the fan nor the heat exchanger was used. In the second case, the fan was used when air conditioning was required, and the heat exchanger was operated constantly at a medium setting. In the third case, the heat exchanger was not used but the circulation fan was operated constantly.

Table 2. Effect of heat exchanger setting and circulation fan use on radon concentrations and working levels in the experimental house.

Heat Exchanger setting	Circulation fan use	Upstairs	Downstairs	Outdoors
		Concentrations, pCi/l		
Off	None	1.52	3.70	0.29
Medium	Periodic	0.80	1.39	0.44
Off	Constant	1.51	1.97	0.26
		Working levels		
Off	None	0.011	0.029	0.005
Medium	Periodic	0.006	0.011	0.005
Off	Constant	0.005	0.007	0.004

In all three cases, radon levels were quite low outdoors. With the circulation fan and heat exchanger off, radon concentrations and working levels were relatively high indoors, particularly downstairs.

When the heat exchanger was operated, radon gas concentrations were reduced by nearly 50 percent upstairs and by over 60 percent downstairs. Radon progeny working levels were reduced by nearly an identical amount. When the circulation fan was operated constantly, radon gas concentrations generally were redistributed rather than reduced. However, radon progeny working levels were substantially reduced. The reduction was even greater than that achieved by heat exchanger operation combined with periodic fan use.

It is important to note the differing mechanisms through which the heat exchanger and circulation fan achieved radon progeny reductions. The heat exchanger reduced progeny levels largely through removal of the parent gas, whereas the circulation fan achieved a similar reduction without this removal. Thus, it appears that the air circulation effect previously noted for IP also plays an important role in radon progeny removal.

Conclusions

Operation of the range exhaust fan was effective in reducing the peak concentrations of combustion gases. Continuous operation of the heat exchanger was more effective in reducing 8-hour average concentrations than short-term peaks. Heat exchanger operation reduced HCHO levels but increased IP levels. Constant operation of the circulation fan was as effective or more so than continuous heat exchanger operation in reducing radon progeny levels.

Acknowledgment

This work is supported by the Electric Power Research Institute under Contract RP 2034-1.

References

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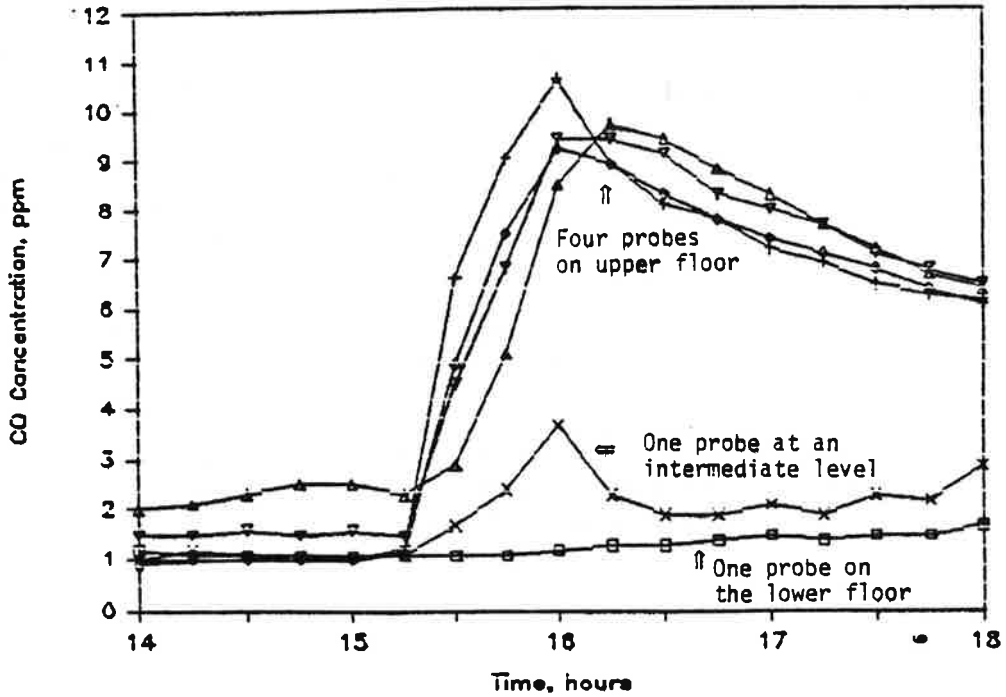

Fig. 2. Effect of heat exchanger flow rate on ratio of experimental/ control HCHO levels.

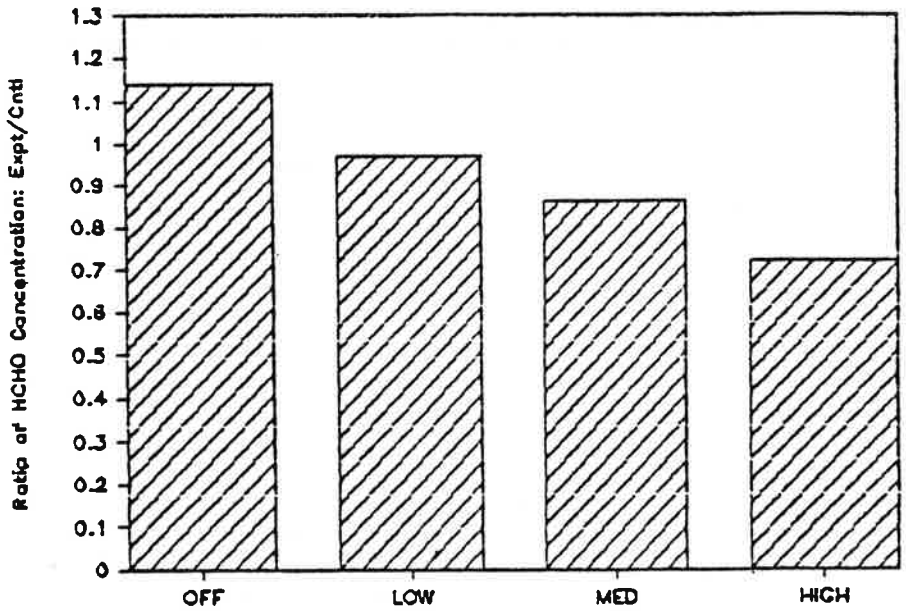

Fig. 1. Horizontal and vertical mixing of carbon monoxide with gas range as indoor source.