

Energy Conservation and Indoor Air Pollution

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Energy conservation measures for buildings work partly by reducing air exchange (v) between buildings and their surroundings, resulting in greater retention of pollutants emitted indoors by combustion and other sources. For example, if v is reduced 4-fold, pilot-light pollutant contribution will quadruple (perhaps rising from ≈ 5 mg/m³ to ≈ 20 mg/m³ for carbon-monoxide). A calculation shows that it might take 4½ h for CO levels to decline below the EPA one-hour ambient standard after only 1 h of oven use in a small kitchen when $v = \frac{1}{4}$ air change/h (ach) but less than ½ h when $v = 1$ ach.

We present a model that accounts for the reduced heating system operating requirement permitted by energy conservation by assuming that indoor pollutant levels are linear in v . This model predicts that when v is reduced 4-fold, heating system pollutant contributions can still rise up to 3-fold, depending upon building characteristics and the extent of increased insulation.

Thus precautions are clearly necessary when tightening building envelopes. At a minimum, pilot lights should be eliminated and effective kitchen ventilation systems installed.

INTRODUCTION

Energy conservation in buildings involves a variety of measures that prevent heat exchange between buildings and their surroundings by actual air exchange (convection) or by conduction and radiation. Storm windows, for example, add an insulating air layer that both reduces conductive heat loss and hinders infiltration, reducing convective heat loss.

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Convection is also the primary method for replacing contaminated indoor air. Consequently building envelopes tightened to conserve energy may also trap increased quantities of pollutants indoors, with possible deleterious effects. (We show elsewhere [1] that tighter envelopes do not significantly protect building occupants against outdoor pollution sources.)

There are many indoor pollutant sources, some involving combustion [2, 3, 4] (heating systems, cooking, smoking) but also chemicals [5] (cleaners, insecticides) and building materials themselves (formaldehyde [6, 7], Rn-222 [8]). In the present paper we predict the effects of tighter building envelopes on indoor pollutant levels, a necessary prerequisite to estimating possible health effects. In order to predict these levels, we derive a mathematical model that accounts for the lower pollutant production rate made possible by the reduced need for heating system operation. We find that in spite of reduced heating system operation, pollutant levels can still be predicted to rise if convection-reducing conservation measures are performed in isolation. In another paper [9] we derive a more detailed heating system model with fewer simplifying assumptions than used here. This model validates the conclusions reached here and also shows that if conservation measures are carried out in a balanced manner, i.e., envelopes are tightened at the same time that sufficient insulation is added, then there need be no increase in heating system-generated indoor air pollution. Pollutants from all other sources, however, will rise in response to tighter building envelopes.

INDOOR POLLUTION MODEL

A widely used model [10] that describes the level p , of any pollutant P , is given by:

$$p' = \frac{dp}{dt} = k - v(p - p_0) \quad (1)$$

where

k = pollutant production rate per unit building volume,

v = air exchange (ventilation + infiltration) rate,

p = indoor pollutant concentration,

p_0 = outdoor pollutant concentration

and all of these except p are assumed constant. We will use eqn. (1) to study the effect of lowering v on pollution generated by cooking. By modifying eqn. (1) we can also predict the effect on heating system-generated pollution.

A solution to eqn. (1) is:

$$p - p_0 - \frac{k}{v} = (p_i - p_0 - \frac{k}{v})e^{-vt} \quad (2)$$

where $p_i = p(0) =$ value of p when $t = 0$.

STEADY-STATE

The long-term steady-state pollutant contribution, p_s , of sources of P may be obtained in two ways. When p has levelled at $p_0 + p_s$, then $p' = 0$ so eqn. (1) yields:

$$p_s = k/v \quad (3)$$

Permitting $t \rightarrow \infty$ in eqn. (2) yields the same result so that eqn. (2) becomes:

$$p - p_0 - p_s = (p_i - p_0 - p_s)e^{-vt} \quad (2')$$

p_s is equal to the sum of the steady-states for each source. As long as k is independent of v , p_s will vary inversely with v . For example, p_s will quadruple if v is cut 4-fold for pollutants produced only by pilot lights or long-term oven use.

HEATING SYSTEM

Let indoor temperature be held constant by thermostat. Let k_h = rate of pollutant production/ building volume, for continuous heating. We assume that when the heating system is the only source of pollutant P :

$$k = rk_h$$

where r = proportion of time that the heating system operates. We can now examine the dependence of r on v and ΔT , the temperature difference between inside and outside.

Even a perfectly sealed box can exchange heat with its surroundings. Thus even if a building were completely sealed, heat would be required to maintain a given temperature. Let a = the length of time the heating system would be required to operate in this case; a depends on the effectiveness of the insulation and on the building geometry. In addition, air must be heated on entering the building; the amount of heat required increases as v does. Assuming that r is linear in v to account for this, then r depends on v and ΔT as follows (ignoring any heat contribution from the sun, people and appliance use):

$$r = r(v, \Delta T) = (a + bv)\Delta T, \text{ if } (a + bv)\Delta T \leq 1 \\ = 1 \text{ otherwise.} \quad (4)$$

b is a constant and also depends on building geometry; both a and b are discussed further elsewhere [9].

We write $p_s = p_{s,v}$ (or $p_s(v)$) since p_s depends on v . From eqn. (3) and (4):

$$p_{s,v} = \frac{k}{v} = \frac{rk_h}{v} \\ = \frac{(a + bv)\Delta Tk_h}{v} = \left(\frac{a}{v} + b\right)\Delta Tk_h \\ \text{for intermittent operation} \\ = \frac{k_h}{v} \\ \text{for continuous operation.} \quad (5)$$

We don't know v , a or b for actual buildings today and we don't know exactly how various conservation measures will affect them. If we assume that by lowering v from 2 to $\frac{1}{2}$ air change/h (ach) without changing a or b , we can cut the fuel requirement of a house by 25%, then $b = \frac{1}{4}a$ h. If this can be done by lowering v from 1 to $\frac{1}{2}$ ach, then $b = a$ h.*

How good are these assumptions? The Princeton University Center for Environmental Studies is presently conducting fuel conservation studies on recently built townhouses in

*Terms always include their units internally; thus, $b = a$ h, means that the units of b are the same as the units of $a \times h$. In this case a has the units $1/^\circ\text{C}$ so b has the units $\text{h}/^\circ\text{C}$.

the Twin Rivers development in New Jersey [11]. In 19 of the houses, fuel savings of 25% were achieved for heating and cooling by retrofitting techniques that included both insulation and a reduction of the air-exchange rate from about 0.6 - 0.8 to 0.3 - 0.5 ach [11 - 13]. In another house, retrofit using even more stringent techniques including a reduction of the air exchange rate to 0.3 ach, fuel savings of 68% were achieved [14]. These fuel reductions are not far from our assumptions, although air-exchange rates were not changed in isolation, but in conjunction with other conservation techniques. It is estimated that when $v = 0.8$ ach, infiltration is responsible for about 1/3 of the heat loss of a house [14, 15]. In our terminology, this means:

$$b \times 0.8 \text{ ach} = \frac{1}{3} (a + b \times 0.8 \text{ ach}) \text{ or}$$

$$b = \frac{5}{8} a \text{ h}$$

which is exactly the midpoint of the range for b that we have assumed.

If we assume that in a completely sealed house ($b = 0$), the heating system would operate continuously only for $\Delta T \geq 80^\circ\text{C}$, then ($a = 1/80^\circ\text{C}$) and for $\Delta T = 20^\circ\text{C}$ there is intermittent operation for $v \leq 12$ ach if $b = a/4$ hr and for $v \leq 3$ ach if $b = a$ hr. We give in Table 1 relative steady-state pollution concentration differences for these two cases for different v , at $\Delta T = 20^\circ\text{C}$. (Our results do not depend on the actual choice of a provided it is small enough to ensure that ΔT is maintained for all v in which we are interested; i.e., v for which $(a + bv)\Delta T \leq 1$.)

TABLE 1

Relative steady-state pollution concentration differences due to heating system operation.

v (ach)	$b = \frac{1}{4}a \text{ h}$	$b = a \text{ h}$
	$\frac{p_s(v)}{p_s(l)}$	$\frac{p_s(v)}{p_s(l)}$
$\frac{1}{4}$	3.4	2.5
$\frac{1}{2}$	1.8	1.5
1	1.0	1.0
2	0.6	0.75

Table 1 shows, for example, that when v is lowered from 1 to $\frac{1}{4}$ ach, p_s does not quadruple but only approximately triples (because at a lower v more pollution is retained by the house although less is produced). Some of the actual ratios may be even larger than given in Table 1; we have assumed complete and instantaneous mixing of all the air inside the house. This is not necessarily true, especially for a large v . In this case, the different air components may not have enough time to mix before being exhausted [10].

We may conclude that while conservation measures that seal a house will enable the heating system to emit pollutants at a lower rate, actual pollutant concentrations will be significantly higher than in a more leaky house.

COOKING

Cooking is usually not continued long enough for p_s to be reached. We will assume that a gas range is used for one hour and ask: "How long does it take (t_a) for p to decline from its level at the end of cooking to some level of interest, p_a (e.g. an ambient air standard)?"

Prior to cooking with a gas appliance, the pilot light has been on, producing a steady-state pollutant concentration difference $p_{s,p}$. Thus, $p_0 + p_{s,p}$ is the initial concentration at the start of cooking. (We shall ignore the contribution to p during cooking of any remaining pilot lights.) Let us assume that cooking is done for one hour. Then by eqn. (2')

$$p(1 \text{ h}) - p_0 = p_{s,c} + (p_{s,p} - p_{s,c})e^{-vh} \quad (6)$$

where $p_{s,c}$ = steady-state concentration difference for cooking. Eqn. (7) is only approximate because air is unlikely to be completely mixed during one hour of cooking.

We now rename our parameters and call $t = 0$ the time when we stop cooking, $p_i = p(1 \text{ h})$ from eqn. (6) and $p_s = p_{s,p}$ because eventually p will decline to $p_0 + p_{s,p}$. Then applying eqn. (2') again gives:

$$p_a - p_0 = p_{s,p} + (p_{s,c} - p_{s,p})(1 - e^{-vh})e^{-vt_a} \quad (7)$$

which is straightforward to solve for t_a .

EXAMPLE

As an example, we shall calculate t_a for [CO] resulting from oven use in a controlled ventilation chamber described by Hollowell *et al.* [3]; the volume is 27 m^3 and v is controlled to $\frac{1}{4}$ ach. The Environmental Protection Agency National Primary Ambient Air Quality Standard for CO is 40 mg/m^3 for 1 h [3], which we take as p_a . To obtain $p_{s,p}$, we multiply by 4 the steady-state CO concentration, 5 mg/m^3 , that Hollowell *et al.* [3] found in a kitchen of unknown volume, in a house with $v = 1 - 2$ ach. We now have:

$$\begin{aligned} p_a &= 40 \text{ mg/m}^3 \\ p(1 \text{ hr}) &\approx 80 \text{ mg/m}^3 \\ p_o &= 1 \text{ mg/m}^3 = 0 \\ p_{s,p} &= 20 \text{ mg/m}^3 \text{ and} \\ v &= \frac{1}{4} \text{ ach} \end{aligned}$$

We still need $p_{s,c}$. Using eqn. (6), we get:

$$80 \text{ mg/m}^3 = p_{s,c} + (20 \text{ mg/m}^3 - p_{s,c})e^{-\frac{1}{4}}$$

or

$$p_{s,c} = 291.25 \text{ mg/m}^3$$

Substituting the above values into eqn. (7), we get:

$$40 \text{ mg/m}^3 = 20 \text{ mg/m}^3 + 271.25 \text{ mg/m}^3 \times 0.2212 e^{-\frac{1}{4}t_a} \text{ or}$$

$$t_a = 4.4 \text{ h}$$

That is, the CO concentration will remain above the one-hour ambient standard for nearly $4\frac{1}{2}$ h after cooking in a small room with $v = \frac{1}{4}$ ach. For $v = \frac{1}{2}$ and 1 ach, $t_a = 84$ and 27 min respectively (based partly on estimates in ref. 17, Tables V and VI; calculations not shown).

DISCUSSION

We have presented a model here that accounts for the reduced heating system operating requirement permitted by energy conservation. In the model we assume that heat loss is linear in v (proportional to $a + bv$); then p_s is proportional to $1/v + b/a$ and not to $1/v$ as for all other indoor pollutant sources. This model predicts that a 4-fold reduction in v could still increase the heating system contribution to indoor pollutant levels up to 3-fold,

the extent of increase depending on building characteristics (a and b) and on the effectiveness of added insulation.

Pollutant levels contributed by pilot lights will quadruple for the same reduction in v (perhaps from $\approx 5 \text{ mg/m}^3$ to $\approx 20 \text{ mg/m}^3$). We calculated that it would take $4\frac{1}{2}$ h for CO levels to decline to the EPA one-hour ambient standard after only 1 h of oven use in the controlled ventilation chamber used by Hollowell *et al.* [3] with $v = \frac{1}{4}$ ach. By contrast, p would decline to p_a after about $1\frac{1}{2}$ h when $v = \frac{1}{2}$ ach and about $\frac{1}{2}$ h when $v = 1$ ach. Pollutant levels after 1 h of cooking are not much lower for $v = \frac{1}{2} - 1$ ach than for $\frac{1}{4}$ ach [17]; the tightened envelope merely retains pollution longer.

Further estimates of combustion-generated pollutant contributions are presented in [17]; unfortunately, the quality of available data on which to base extrapolation to lower v — and to evaluate health implications — is very poor. However, it is clear that tightened building envelopes can result in significant air quality deterioration. Thus precautions are necessary, as discussed in greater detail elsewhere [1, 9]. At a minimum, pilot lights can be eliminated and effective kitchen ventilation systems installed.

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