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Abstract

Formaldehyde is a common indoor air pollutant that is difficult to control. One potentially suitable control technique for indoor formaldehyde is air washing: the absorption of formaldehyde by a liquid. In this report we present a mathematical model of an air washer, describe tests of two air washers, and compare the energy required for controlling formaldehyde concentrations by ventilation and by air washing. The two experimental air washers tested employed water as the washing liquid and incorporated a refrigeration system to control the humidity of the outlet airstream. Air flow rates through the air washers were 100-160 ℓ/s and inlet formaldehyde concentrations were 80-480 ng/ℓ. The formaldehyde removal efficiencies of the two designs were 0.36-0.47 and 0.30-0.63. Results show that an air washer with reasonable power and water requirements can effectively remove formaldehyde from indoor air.

Introduction

One technique for the control of indoor formaldehyde concentrations which has not been previously investigated is air washing. In an air washing process, an airstream contaminated with a gaseous pollutant is brought into contact with a washing solution and the pollutant is dissolved into the solution. To investigate the feasibility of air washing for indoor formaldehyde control we have designed and fabricated two full-scale air washers and evaluated their performance with the aid of a unique test system. In this report we present a mathematical model of an air washer, describe the air washer tests, and compare the energy required for controlling formaldehyde concentrations by ventilation and by air washing. More detailed information is available in (4).

Air Washer Model

The model presented below reflects the design of the experimental air washers. Water, the washing solvent, was recirculated through an airstream so that the concentration of formaldehyde in the washing solution was approximately uniform throughout the air washer. A portion of the washing solution was continuously replaced with fresh, formaldehyde-free water to prevent saturation of the solution with formaldehyde.

Figure 1 is a schematic of the control volume employed for derivation of the one-dimensional model. The formaldehyde mass balance equation for the element shown is

$$QC(x) - Q[C(x) + (dC/dx)dx] = [C(x) - C_e](h_d A/L)dx \quad (1)$$

where:

- Q = volumetric air flow rate,
- $C(x)$ = concentration (mass/volume) of formaldehyde in air in a plane located a distance x from the air washer inlet,
- C_e = concentration of formaldehyde in air that would be in equilibrium with the washing solution,
- A = total air-solution interface area,
- L = length of air washer in the x direction, and
- h_d = mass transfer coefficient.

The term C_e accounts for the concentration of formaldehyde in the solution. We have assumed C_e to be constant and independent of x.

We define two measures of air washer efficiency: a "formaldehyde removal efficiency", ε_1 , and an "air washer device efficiency", ε_2 ,

x
$$\varepsilon_1 = (C_{in} - C_{out}) / C_{in} \tag{2}$$

x
$$\varepsilon_2 = (C_{in} - C_{out}) / (C_{in} - C_e) \tag{3}$$

where C_{in} and C_{out} are the formaldehyde concentrations at the air washer inlet and outlet, respectively. By solving Equation 1 for C_{out} we derive the expressions

x
$$\varepsilon_1 = [1 - \exp (h_d A/Q)][1 - C_e/C_{in})] \tag{4}$$

x
$$\varepsilon_2 = 1 - \exp (h_d A/Q) \tag{5}$$

The device efficiency, ε_2 , is also the first term in the formaldehyde removal efficiency expression (Equation 4). The second term in this expression accounts for the effect of the driving potential for mass transfer on ε_1 .

The quantity C_e can be related to the concentration of dissolved formaldehyde in the washing solution, C_s, by Henry's law

$$C_e = K(T)\ C_s \tag{6}$$

where K(T) is a proportionality constant dependent on temperature. Values of K(T), 2.1-7.1 torr/mole fraction for 5-20^{o}C, are given in (1). The quantity C_s depends on the rate at which formaldehyde is removed from the air and the rate at which the washing solution is replaced with fresh water

x $$C_s = \varepsilon_1 C_{in} Q/R \tag{7}$$

where R is the solution replacement rate.

Experimental

The two air washers utilized the same case to hold the air-solution contact arrangements and additional components common to each air washer. The insulated stainless steel case included a chamber for air-solution contact (0.71x0.56x0.56 m) and a sump (30 ℓ capacity). To control the humidity of the outlet airstream, the air was cooled prior to contact with the washing solution; this ensured that the air leaving the air washer had a low humidity. The evaporator coil of a 4.0 kW (output) refrigeration system was mounted upstream of the contact chamber and the condenser coil was located downstream. A pump was employed for replacement of the washing solution in the sump with fresh water. The two air washers were distinguished by their air-solution contact arrangements. The arrangement for Air Washer No. 1 consisted of rotating foam mats. The airstream passed through pores in the mats; the mats were maintained wet by rotation through the solution in the sump. Air Washer No. 2 was based on a commercial mass transfer media. A pump sprayed solution from the sump over the media surfaces.

The formaldehyde removal performance of the air washers was evaluated by supplying an airstream with a controlled formaldehyde concentration to the air washers and measuring the inlet and outlet formaldehyde concentrations. The test system is described in (5). The formaldehyde concentration of the air was determined by drawing a sample airstream through chilled, water-filled impingers and subsequently analyzing the water by the modified pararosaniline method (3). The formaldehyde concentration of the washing solution was also measured by this method.

The test procedure was designed to evaluate the air washers under steady-state conditions. Steady-state was achieved when the rate of formaldehyde removal from the air equalled the rate of formaldehyde removal from the sump by the washing solution replacement process. Prior to steady-state operation the formaldehyde concentration of the solution would be lower than the steady-state value, thus, as may be seen from Equations 4 and 6, the formaldehyde removal efficiency of the air washer would be artificially high. In fact, for most tests steady-state conditions were not achieved so the air washer model was employed to correct the data to steady-state conditions.

For tests of both air washers, relevant parameters were varied for each test to assess their impact on air washer performance. To demonstrate that the materials from which the air washers were fabricated did not, at steady-state, remove formaldehyde from the air, background tests were run with each air washer. To conduct these tests, the washing solution was removed and the refrigeration system was not operated.

Results and Discussion

Formaldehyde Removal Performance

The test results and significant test condition data are listed in Table 1. The corrected formaldehyde removal efficiency, ε_1^*, is the predicted steady-state removal efficiency calculated from the nonsteady-state test results using the mathematical model. These corrected efficiencies were 0.36-0.47 and 0.30-0.63 for tests of Air Washers No. 1 and No. 2, respectively. The measured (i.e., uncorrected) formaldehyde removal efficiencies were generally higher but could be achieved under steady-state conditions by increasing the rate of washing solution replacement. The mathematical model was also employed to calculate the air washer device efficiency, ε_2. The effective clean air flow rates listed in Table 1 are the product of ε_1^* and the air flow rate through the air washer. This parameter represents the equivalent flow of formaldehyde-free air that is provided by the air washer. Some of the variations in the tabulated results are due to differences in test conditions or other effects which are not noted here.

Table 1. Results of Air Washer Tests.

Test No.[1]	Air Flow Rate (ℓ/s)	Inlet [HCHO][2] (ng/ℓ)	Washing Solution Replacement Rate (ℓ/hr)	Efficiencies[3] ε_1	ε_1^*	ε_2	Effective Clean Air Flow Rate (ℓ/s)
1-1	98.3	467	3.0	0.57	0.44	0.60	43
1-2	101	148	1.7	0.55	0.41	0.64	41
1-3	145	94.2	7.9	0.36	0.36	0.38	52
1-4	119	116	7.6	0.42	0.41	0.44	49
1-5	119	106	4.5	0.40	0.40	0.44	48
1-6	118	218	7.4	0.42	0.42	0.45	50
1-7	119	222	5.7	0.49	0.47	0.53	56
1-8	120	250	4.1	0.38	0.36	0.40	43
1-9	157	360	4.1	0.38	0.36	0.41	57
1-B	120	294	---	0.00	---	---	0.0
2-1	117	269	2.3	0.77	0.63	0.93	74
2-2	117	252	2.3	0.68	0.56	0.81	66
2-3	160	84.6	1.7	0.65	0.46	0.78	74
2-4	116	79.7	1.4	0.70	0.51	0.86	59
2-5	116	161	2.3	0.72	0.60	0.84	70
2-6	116	102	0.66	0.74	0.35	0.89	41
2-7	116	136	0.54	0.63	0.30	0.77	35
2-B	116	143	---	0.02	---	---	2.0

1. "1-" and "2-" denote Air Washer No. 1 and No. 2 tests, respectively. "-B" denotes background tests.
2. [HCHO] is formaldehyde concentration in air (25°C, 1 atm).
3. ε_1 is measured formaldehyde removal efficiency, ε_1^* is corrected formaldehyde removal efficiency, and ε_2 is device efficiency.

The mass transfer coefficient - interface area product, h_dA, was also calculated from the model for each test. For Air Washer No. 1 the range of this product was 62.0-103 ℓ/s and for Air Washer No. 2 the range was 172-304 ℓ/s. Similar or higher formaldehyde removal efficiencies were achieved with Air Washer No. 2 despite generally lower solution replacement rates because of higher h_dA values.

Energy Comparison of Ventilation and Air Washing

At present, ventilation is the most readily available control technique for existing residences with unacceptable formaldehyde concentrations. To compare the energy requirements of ventilation and air washing we have calculated the energy required to provide a 90 ℓ/s effective clean-air flow rate to a residence by three different means: natural ventilation, mechanical ventilation with an air-to-air heat exchanger (MVHX system), and air washing. The calculations are for electrically-heated residences located in two different climates and assume continuous ventilation or air washing during a seven-month heating season. The energy requirements of the two ventilation strategies were calculated from data in (2). The power requirement of an air washer has been estimated to be 1800 W (4). Unlike ventilation, air washing does not increase a residence's heating load. In fact, because the energy consumed by the air washer is returned to the indoor space, it reduces the heating load when outdoor temperatures are sufficiently low. Thus, the net energy required for air washing equals the energy required to operate the air washer minus the heating load offset. The results of the comparison are shown in Table 2.

Table 2. Energy Comparison of Ventilation and Air Washing.

		Energy, GJ	
		Minneapolis, MN	Chicago, IL
Energy Requirements	Natural Ventilation	47.7	34.9
	MVHX System [a]	14.9	11.6
	Air Washer	33.0	33.0
Air Washer Operation	Heating Load Offset	27.0 (0.82[b])	25.0 (0.76[b])
	Net Energy Requirement	6.0	8.0

a. Mechanical ventilation system with an air-to-air heat exchanger.
b. Fraction of heating season that air washer energy consumption will offset the residence's heating load.

The net energy requirement for air washing is less than the energy requirements of either of the ventilation strategies in both climates. In residences which use forms of heating energy that are less expensive than electricity, the heating load offset caused by operation of an air washer is less advantageous so the other strategies may be preferred.

Conclusions

The results of this study show that an air washer can effectively remove formaldehyde from indoor air. Higher formaldehyde removal efficiencies could be achieved with future designs. The water requirement of an air washer is reasonable and the power requirement will be acceptable in some situations, particularly in electrically-heated buildings. Air washing may also be an attractive technique to reduce formaldehyde concentrations in some occupational settings, particularly when it can be easily integrated into existing air handling systems.

We have not attempted to predict the impact of air washer operation on indoor formaldehyde concentrations. Further study is needed to quantify the relationships between formaldehyde source strengths, removal rates, and indoor concentrations. In many cases, the formaldehyde source strength will increase significantly as the indoor concentration is reduced, therefore, large amounts of ventilation or air cleaning will be required to substantially reduce indoor formaldehyde concentrations. Future investigations of air washing or other air cleaning techniques for formaldehyde control should be directed toward developing air cleaners with even larger air flow rates, as well as lower power requirements, than the devices described here.

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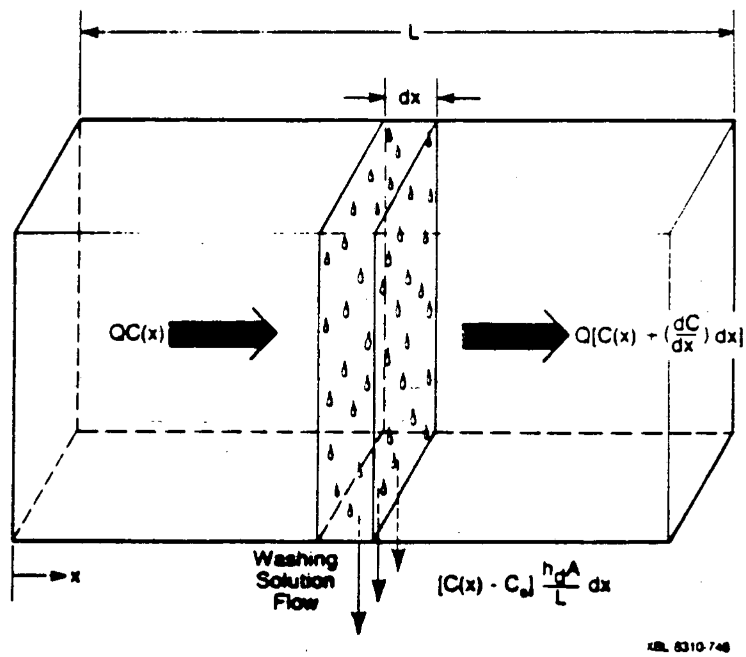

Figure 1. Schematic diagram of control volume employed for derivation of the air washer model. Nomenclature is presented in the text.

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