The Feasibility of Using a Photoelectric Cigarette Smoke Detector for Energy-Efficient Air Quality Control

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ABSTRACT

The object of this study was to determine the feasibility of using a smoke sensor to monitor and control cigarette smoke levels in occupied spaces and also to determine whether the use of such a detector could result in energy savings. A smoke detector was built and tested. The experimental results show that the smoke sensor output is a function of cigarette smoke concentration and that the smoke sensor gives a rapid and continuous response. In addition, a computer program that simulates the transient mass and energy interactions in buildings was modified so that the impact of ventilation strategies on indoor air quality and energy consumption could be studied when smokers are present. The results of the numerical modeling for an arbitrary test case show that the use of a smoke sensor to detect cigarette smoke particulates and to control ventilation can allow indoor air quality to be continuously maintained at acceptable levels while minimizing energy consumption.

INTRODUCTION

Mechanical ventilating systems usually provide a fixed minimum quantity of outdoor air while recirculating some of the indoor air. The fixed quantity of outdoor air is based on a maximum number of people, and where smoking is allowed, this quantity can be as much as five times the quantity required for nonsmoking, as suggested by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62-1981. Based on the data obtained by Cain et al. (1981), the ASHRAE recommendations for smoking occupancy are too low to control either odor levels or particulate concentrations assuming full occupancy. As a result, the quantity of outdoor air required for a smoking area in which acceptable indoor air quality is to be maintained may be much higher than five times that for a nonsmoking area. In another study (Jones and Fagan 1974), it was found that a room with smokers would require a rate of ventilation ten times higher than that of a same room with nonsmokers in order to maintain acceptable carbon monoxide concentration levels. Also, when a space is occupied by fewer people than the maximum, energy is wasted to heat or cool the additional outdoor air. On the other hand, when the number of people exceeds the design maximum or if the indoor air is only recirculated (and not correctly treated), in the presence of many smokers, the indoor air quality may be totally unacceptable and deleterious to both smokers and nonsmokers. The use of filters and washers to remove all of the objectionable particulates and gases is expensive.

To alleviate the above problems, the ventilation rates of a space can be controlled by installing a sensor that is sensitive to cigarette smoke (and therefore sensitive to the

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number of smokers). The output of such a sensor can be used to control the amount of outdoor air and hence the tobacco smoke in a space. As a result, considerable energy can be saved while maintaining acceptable indoor air quality.

An air quality sensor must meet the following requirements (Turiel et al. 1979):

1. Sufficient sensitivity to detect and measure changes in the range of concentrations required for ventilation rate control

2. No significant interferences

3. Continuous measurement capabilities

4. Instantaneous readout

5. Automatic operation

6. Low maintenance

7. Low cost

Two independent studies (Unpub. report 1981; Sodergren and Punttila 1983) showed that carbon dioxide can be used as the basis for controlling ventilation rates. However, because of the relatively high first costs of carbon dioxide detectors, such a sensor can only be justified in buildings with high and irregular occupancy.

The present research has shown that the sensor of a low-cost conventional smoke detector can be used to detect cigarette smoke in the concentrations of interest. Such a detector would meet the above-listed requirements.

PRINCIPLE OF OPERATION

Light scattering is a technique that can be used for continuous, nondestructive detection of cigarette smoke. For aerosols in the size range of tobacco smoke, the simplified Mie's Equation (Green and Lane 1957) relates the light scattered by an aerosol to the particle concentration of the aerosol:

$$I = k\, r^p\, n \tag{1}$$

where

I = scattered light intensity

n = particle number concentration

r^p = radius of particles raised to some power p

k = proportionality constant

If the scattering angle, the wavelength of incident light, and the average particle radius are assumed to be constant, then it can be concluded from Equation 1 that the intensity of the scattered light is directly proportional to the number of particles per unit volume.

Thus, a light-emitting diode, LED, and a phototransistor can be positioned at an angle to each other so that when there is no smoke the light emitted from the LED bypasses the cell. But, when smoke particles are present, they scatter the light from the LED onto the light sensor as shown in Figure 1.

EXPERIMENTAL PROCEDURE

A smoke sensor was constructed for testing, using the case of a photoelectric detector. The light-emitting diode, LED, used for obtaining experimental data was a gallium aluminum arsenide, super high output, infrared-emitting diode, and the light sensor was a silicon phototransistor. The phototransistor-LED circuit is shown in Figure 2.

The test chamber where the smoke was sampled is the 66 × 19 × 18 in.^{3} (1.71 × 0.53 × 0.50 m^3) chamber suggested by the Underwriters Laboratories for sensitivity tests of smoke detectors (UL 1980) (see Figure 3). A cigarette (king size, filter, hard pack) was lighted and introduced in the test chamber while the circulation fans were running. A small fan was also placed next to the smoke detector to assure uniformity of flow. The block diagram of the experimental setup is shown in Figure 4.

Smoke samples were taken at one-minute intervals. An aerosol particle counter was used for measuring the cigarette smoke concentration. The response of the phototransistor was obtained by measuring the current of the phototransistor circuit with a high-speed picoammeter. The output of the picoammeter was amplified and recorded on a datalogger at one-minute intervals. A thermocouple was used to measure the dry-bulb temperature, and the dew point was obtained with a dew-point hygrometer. A more detailed description of the experimental setup can be found in Alevantis (1984).

EXPERIMENTAL RESULTS

The experiment was repeated several times before the final data were taken. Figure 5 shows the results of the last two runs. The relationship between the output (in nanoamperes) of the phototransistor, NA, and the output voltage of the amplifier, V, is NA = 6.356 + 0.6474 V. Observations during the experiments indicate that the smoke detector gives a rapid response and continuous readout as expected for photoelectric and electronic components. Figure 5 shows that the detector output is a monotonic function of smoke concentration (number/m^3) as predicted by the approximation of the Mie's equation (Equation 1). The difference in the curves for experiments 1 and 2 as seen in Figure 5 could be due to a zero shift caused by the electronics or due to deposition of tobacco smoke on the phototransistor or LED. If the smoke particle density (about 1 g/m^3) and particle size distribution remain constant, then the smoke mass concentration (μg/m^3) will also directly affect the smoke sensor output. The smoke mass concentrations are compared with ASHRAE Standard 62-1981 in the numerical modeling.

The experimental results of Gayle et al. (1979) also showed a direct relationship between smoke concentration and detector output. Gayle et al. also experimentally determined that the light sensor output is independent of the natural tobacco smoke composition, that aging of cigarette smoke has little effect on the sensor response, and that agglomeration produces small changes in sensor response.

NUMERICAL MODELING

Description of Computer Program

The dynamic digital computer program developed at Iowa State University (Samuelson 1983) simulates the transient mass and energy interactions in buildings. The program is capable of handling combinations of mechanical components, building elements, arbitrary weather data, and other inputs. Subroutines were added to the existing program to assess the impact of ventilation strategies on indoor air quality and energy consumption when smokers are present.

Simulation Studies

The computer program was run for a simple, arbitrary, one-room residential building with a height of 12.5 ft (3.8 m) and a floor area of 1550 ft^2 (144 m^2) as shown in Figure 6. The supply and return ducts were 65.6 ft (20 m) in length with a cross-sectional area of 2.7 ft^2 (0.25 m^2). The area of the walls was 1960 ft^2 (182.4 m^2) with a U-value of 0.085 $Btu/hr \cdot ft^2 \cdot F$ (0.48 $W/m^2 \cdot °C$). The inside temperature was maintained at 70° F (21° C) and the average outside temperatre was 19° F (-7° C) giving an average envelope heat loss of 8540 Btu/hr (2.5 kW). Cigarette smoke generation was 0.077 lb/min (0.035 kg/min), which is equivalent to one smoker in this room. The heat pump power was 67 HP (50 kW) (when on), and the fan power was 0.05 HP (40 W) (always on, so that smoke concentration at the return element of the mixed air controller could be detected). The mixed-air air controller adjusted the percentage of outdoor air based on the air quality detected at the exhaust of the room. The percentage of outdoor air (PCOA) was calculated by:

$$PCOA = MINOA + \left(\frac{C_{ret} - C_{min}}{C_{max} - C_{min}}\right)(1 - MINOA) \quad (2)$$

where

MINOA = minimum percentage of outdoor air

C_{ret} = smoke concentration in the return air ($\mu g/m^3$)

C_{min} = smoke concentration below which minimum outdoor air is used

C_{max} = smoke concentration at which 100% outdoor air is used (260 $\mu g/m^3$ as in ASHRAE Standard 62-1981)

Cases were run with and without the smoke detector for different intermittent smoking periods. Intermittent smoking period is the percentage of time when there is smoking during a period of one hour (i.e., an intermittent period of 0.2 means that there is smoking for 0.2 × 60 = 12 minutes every hour). With the smoke detector on, each intermittent smoking period case was run for different minimum control values of smoke concentration. Each intermittent smoking period case without the smoke detector was run for different fixed percentages of outdoor air, as seen in Table 1.

For initialization purposes, the program was run for two days, with the results of the second day presented here. It was assumed that there was no smoking from 22:00 to 8:00 hours. For each case run, the cigarette smoke concentration of the occupied space and the incremental energy consumed were output at each time step. The results were averaged over half-hour periods and plotted against time. In addition, the total 24-hour energy consumed and an average 24-hour cigarette smoke concentration were output for each case, as shown on Table 1. Further details on the numerical modeling can be found in Alevantis (1984).

Numerical Results

Figure 7, which is a summary of all the cases run, shows that when the smoke detector is on, the optimal indoor air quality can be maintained with the lowest energy consumption. When a smoke detector is not used, a low smoke concentration can be maintained by continuously introducing a fixed quantity of outside air in the occupied space, resulting in high energy costs. There is always a trade-off between air quality and energy consumption, but the use of a smoke detector to control ventilation allows air quality to be maintained at acceptable levels while minimizing energy consumption, even when smoking patterns vary.

CONCLUSIONS

The conclusions resulting from the experimental procedure are:

1. The smoke detector current output is related directly to cigarette smoke concentration.

2. The smoke detector gives a rapid response and a continuous readout. The response time is limited only by the response time of the electronic components.

3. Deposition of cigarette smoke on the phototransistor or the light-emitting diode could result in changes of the zero setting of the device.

4. The smoke detector should be placed at a location that is sensitive to the cigarette smoke concentration of the occupied space (i.e., return air duct), so that changes in the cigarette smoke concentration will be immediately detected.

Specific conclusions that resulted from the numerical modeling are:

1. When a smoke detector is used, the optimal indoor air quality can be maintained with the lowest energy consumption.

2. When a smoke detector is not used, a low smoke concentration can be maintained by continuously introducing a fixed quantity of outdoor air in the occupied space, resulting in high operating costs.

3. Although there is a trade-off between indoor air quality and energy consumption, the use of a smoke sensor to detect cigarette smoke particulates and to control ventilation allows indoor air quality to be continuously maintained at acceptable levels while minimizing energy consumption.

In most cases, filtering and washing the recirculated air would be an expensive alternative to using outdoor air to maintain indoor air quality when there are a large number of types of contaminants to be controlled, such as those resulting from smoking tobacco. The use of a smoke sensor to control ventilation then makes good sense. This study has shown that a low-cost detector can be built and would be useful, but some more development work would be necessary to solve the zero drift problem.

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ACKNOWLEDGMENTS

The authors wish to thank Dr. James E. Woods for his suggestions, from which resulted the initiation of this study. Further thanks are due to the office of the Vice-President for Research at Iowa State University and the Iowa State University Engineering Research Institute for the funding of this work.

TABLE 1

Cases Run for Numerical Modeling

Case No.	Smoke Detector	Intermittent Smoking Period	Percent Outdoor Air[a]	C_{min}	C_{avg}	Total Energy
				$\mu g/m^3$		MJ/day
0	Yes	0.2	10	50	81.71	200.0
1	Yes	0.2	10	250	126.8	164.4
2	Yes	0.2	10	2.6	72.36	226.2
3	Yes	0.2	10	0	71.96	227.7
4	Yes	0.5	10	50	154.19	287.1
5	Yes	0.5	10	250	185.58	252.1
6	Yes	0.5	10	0	148.14	304.3
7	Yes	1.0	10	50	271.0	392.0
8	Yes	1.0	10	250	276.16	387.3
9	Yes	1.0	10	0	269.37	395.0
10	No	0.2	10	N/A	491.22	109.1
11	No	0.2	25	N/A	200.0	206.1
12	No	0.2	50	N/A	102.44	358.1
13	No	0.2	90	N/A	58.98	561.2
14	No	0.5	10	N/A	1228.03	109.1
15	No	0.5	25	N/A	499.87	206.1
16	No	0.5	50	N/A	256.11	358.1
17	No	0.5	90	N/A	147.45	561.2
18	No	1.0	10	N/A	2455.81	108.8
19	No	1.0	25	N/A	999.72	206.1
20	No	1.0	50	N/A	512.22	358.1
21	No	1.0	90	N/A	294.89	561.2

[a]Minimum percent outdoor air for cases with smoke detector.

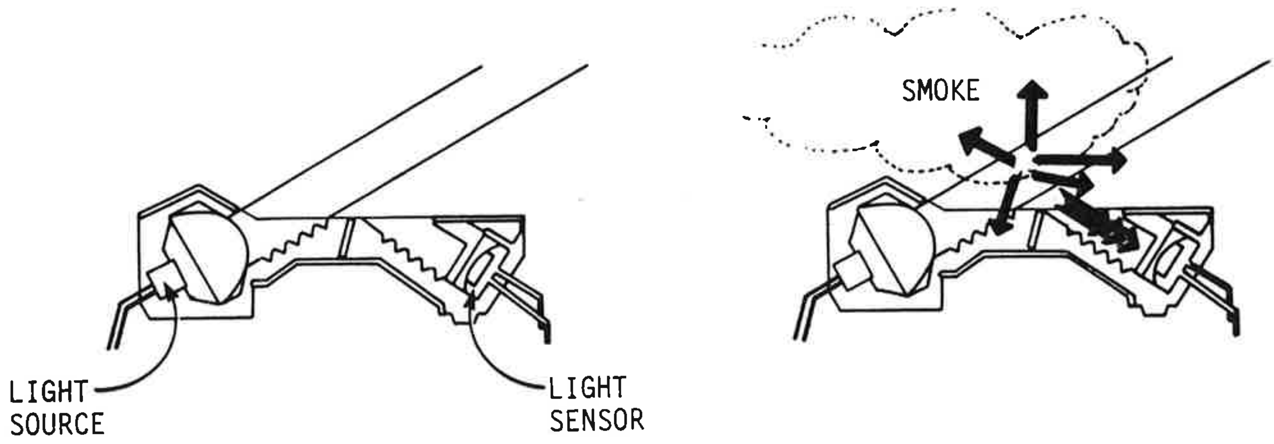

Figure 1. Light scattering technique used in a LED-phototransistor cell

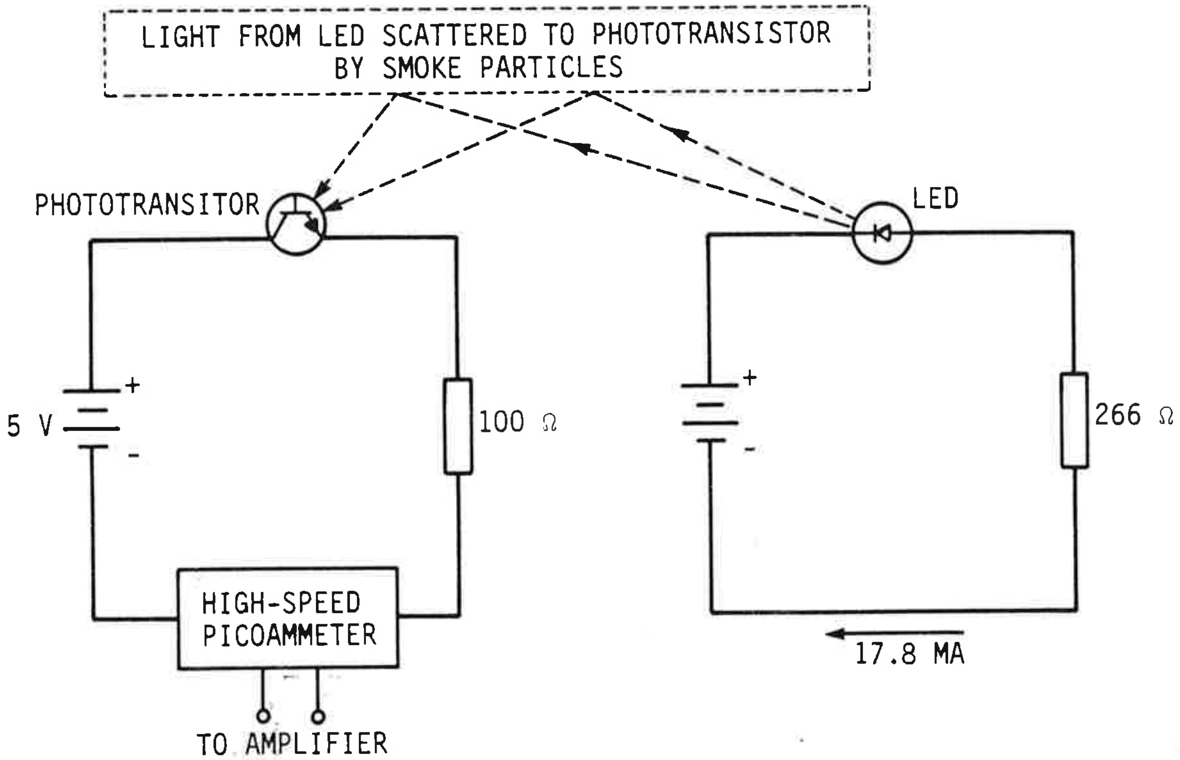

Figure 2. Schematic of smoke sensor electronics

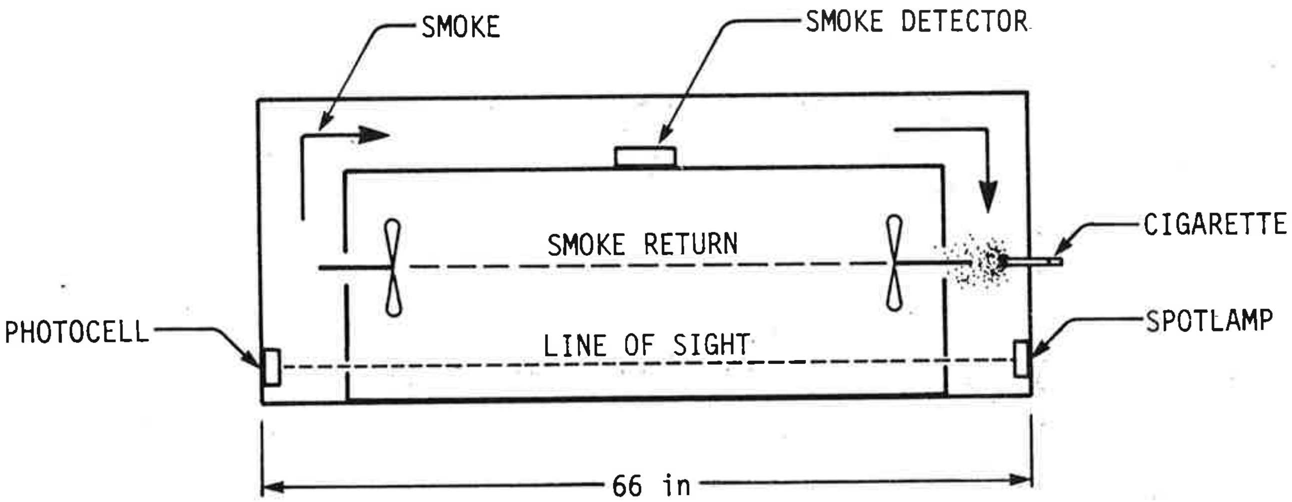

Figure 3. Schematic of test chamber

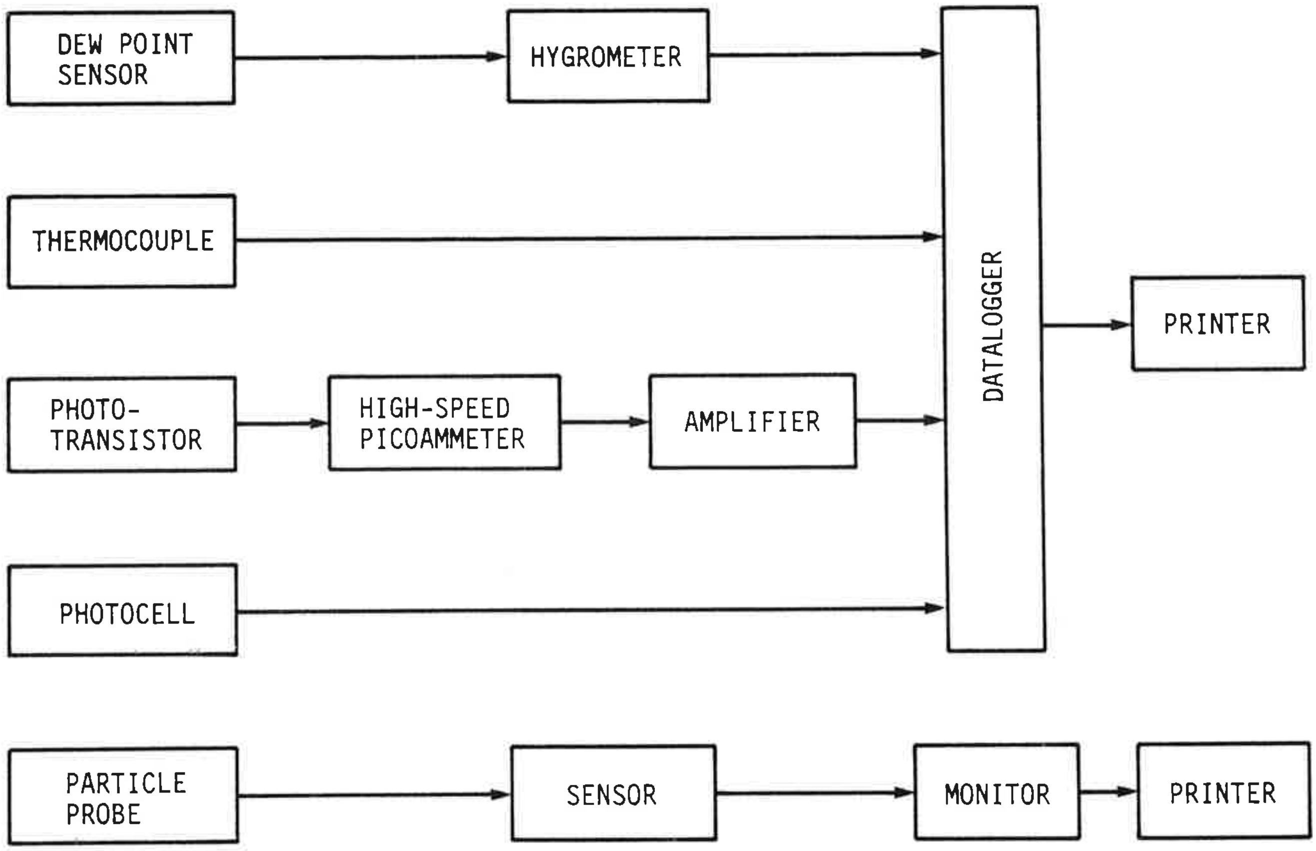

Figure 4. Block diagram of experimental apparatus

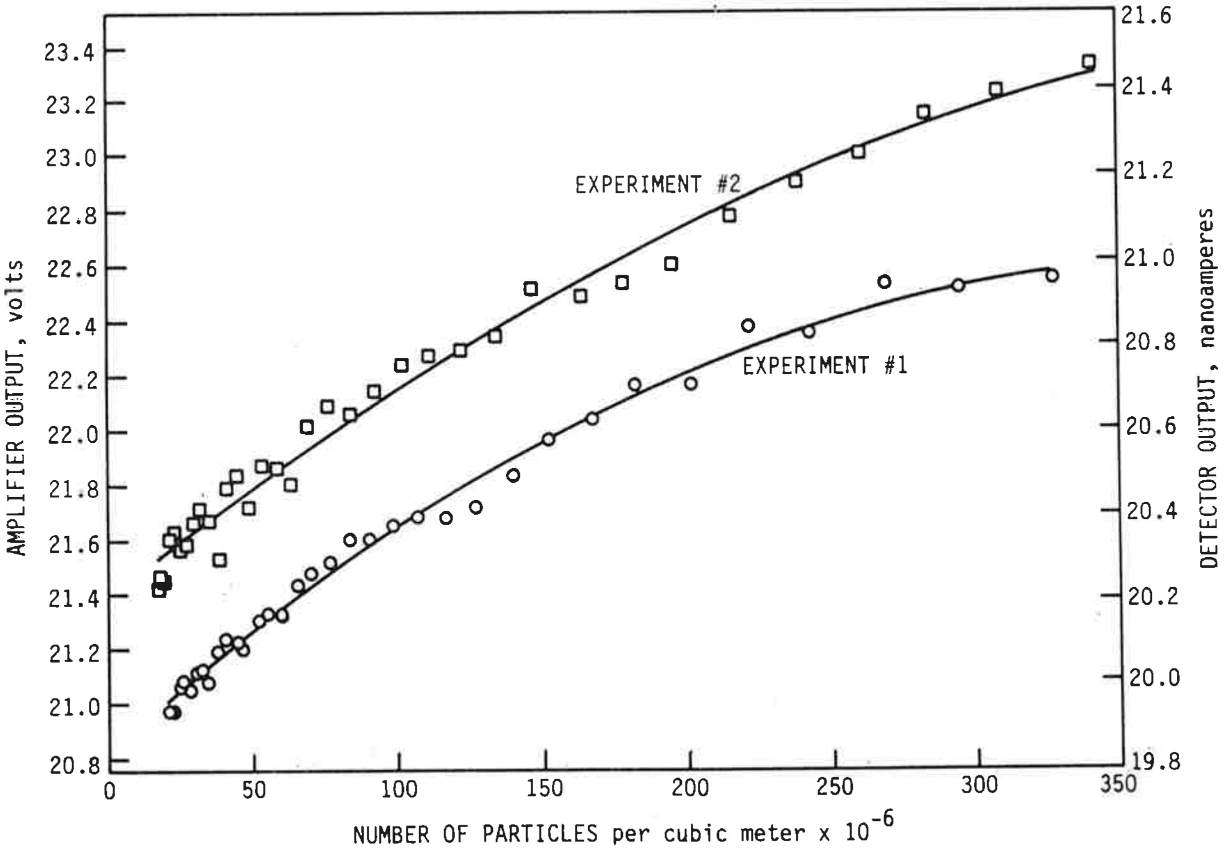

Figure 5. Correlation of photocell response with condensation nuclei concentration for experiments number one and number two

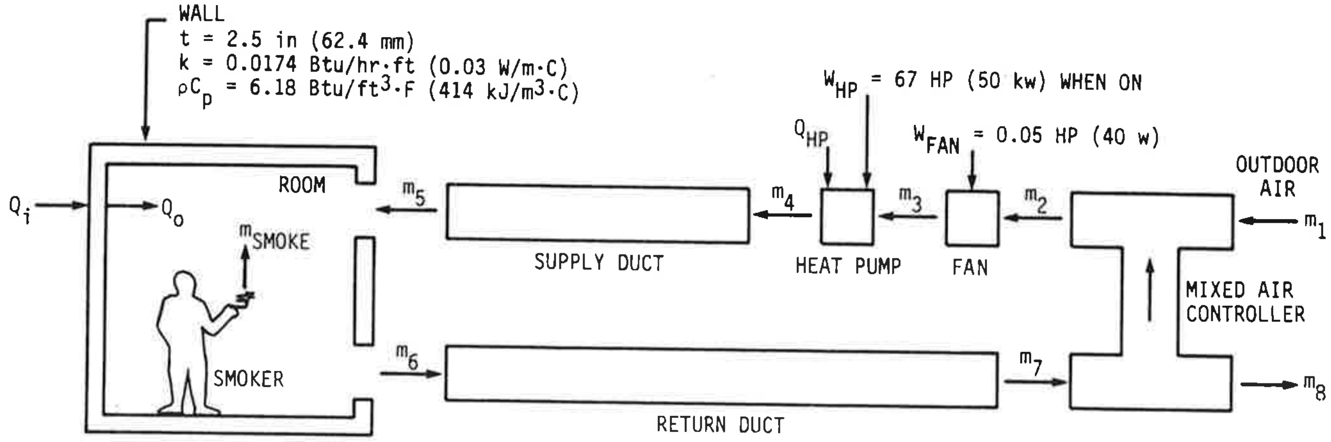

Figure 6. Schematic of elements used in numerical modeling

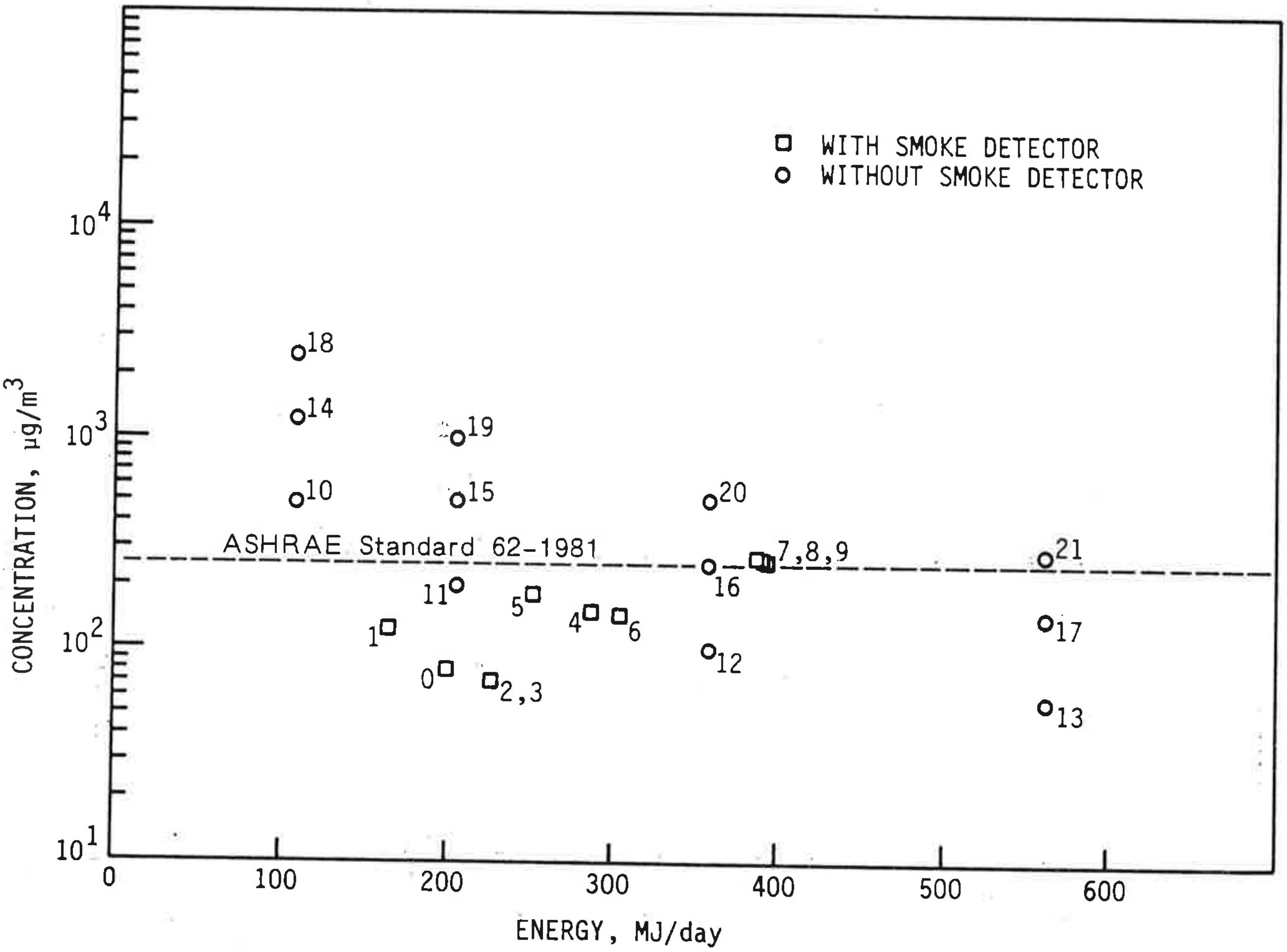

Figure 7. Average smoke concentration versus daily energy consumption for the cases run (100 MJ/Day = \$2.00/Day at 7.2¢/kWhr)