The effect of smoking on ventilation requirements

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Abstract

Suspended particulate matter (SPM), carbon monoxide and droplet nuclei has been measured in a climate chamber of 5o m^3 as indicators of the particulate and gaseous phase of cigarette smoke. Various combinations of smoking intensities and ventilation rates between 1 and 16 air changes per hour were investigated partly by a standardized smoking machine procedure and by individual smoking by a panel of four persons. The panel had at the same time a questionnaire to complete about subjective votes on odour intensities, and irritation to the upper airways and eyes caused by the tobacco smoke.

The results demonstrate that each characteristic component in the cigarette smoke will follow its own elimination function, dependable on adsorption to surfaces, agglomeration or other interaction processes in the enclosed aerosol.

A ventilation rate of 6o-8o m^3 per cigarette smoked seemed to be necessary to eliminate the total aerosol predominantly by ventilation.

The results of the subjective voting on eye and nose irritation, odour intensity and odour pleasantness showed that odour intensity was increasing before irritation, and nose and throat irritation was occurring before eye irritation, but after eye irritation had started, it was given the highest score of irritation degree.

A log-log delineation of connection between concentrations of SPM, CO and condensation nuclei, smoking intensities of 6, 12 and 24 cigarettes per hour and ventilation rates between 10^{-1} and 10^{2} air changes per hour has been made based on extrapolation of experimental data.

Introduction

Enlarged ventilation is needed in enclosed spaces, where tobacco smoking takes place particularly in order to protect the non-smoking occupants against the acute irritation of tobacco smoke on eyes and nose and its annoying smell. This is a question of evaluating comfort criterias for environmental hygiene standards. The question on long term effects of non-smokers exposure to air pollution from tobacco smoke (passive smoking) has been mentioned but not yet considered as a problem giving raise to standard settings. Topical considerations on reduction of ventilation rates in order to meet energy conservation requires in housing, gives meanwhile a renewed interest to focus on both comfort and health and safety questions related to any indoor atmospheric exposure.

Yaglou (1) investigated climatic comfort and annoyance with respect to tobacco smoke and utilized a sensory scale using categories as imperceptible, not objectionable, acceptable, objectionable, endurable and intolerable. This scale has been widely adapted in later investigations and has been found convenient for use in air conditioning engineering too.

Kerka and Humphreys(2) indicated that odour perception of cigarette smoke is affected by environmental temperature and humidity and found, that an increase in humidity at constant dry bulb temperature has the definite effect of lowering the odour intensity levels of cigarette smoke as well as that of pure vapours. The irritation was found to be greatest at low relative humidities. An increase of temperature at constant specific humidity lowered the intensity levels of cigarette smoke odour only slightly. While the perceptible odour level decreased with time of exposure caused to physiological adaptation, irritation to eyes and nose generally increased.

Johansson and Ronge (3) confirmed those findings in experiments using smokers as well as non-smokers as panel, and related the subjective voting to concentrations of total particulate matter in the air. The ventilation required to avoid eye-irritation in the non-smokers was calculated to 12 m^3/h per cigarette, for nose-irritation to 32 m^3/h per cigarette and for annoying smell to 5o m^3/h per cigarette in dry and warm air (25°C, 33% RH).

In more recent studies the general concept has been to determine the identity of the pollutants inhaled with reference to the ambient air quality standards for carbon monoxide and suspended particulate matter (4) or standards for occupational exposure for acroleine and formaldehyde (5). The evaluation of reduced threshold limit values for continuous exposure of the population at large for indoor emissions adding pollutants to the pre-existing burden of airborne contaminants seems to be a need for the future (6).

This study describes in particularly the different relationships between smoking intensity and ventilation rate to concentrations of particulate and gaseous phase in the room air. Discrimination between results obtained by standard smoking performed by smoking machine and by individual smoking has been made in addition as well as subjective judgements by the smoking panel has been recorded.

Methods and Material

The experiments were made in a climate chamber of 5o m^3 with surfaces of aluminium at the Institute of Hygiene, University of Aarhus (7). The temperature varied between 2o ± 1°C and the relative humidity between 65% ± 5% corresponding to a water vapour content of 9-1o g H_2O/kg dry air. This conditions equals the CORESTA-standard for storing and testing cigarettes. The ventilation rate was varied between 1 and 16 air changes/h in accordance to the experimental conditions (table 1).

Table 1. Experimental combination of smoking procedures, smoking intensities and ventilation rates.

Smoking procedure	Number of cigarettes smoked/h	Volume rate of ventilation m^3/h	Number of air changes
Smoking machine according to CORESTA-standard	6	5o	1
	6	1oo	2
	6	2oo	4
	6	4oo	8
	12	45o	8
	24	2oo	4
	24	1oo	2
Individual smoking	4	4oo	8
	4	8oo	16
	12-24	1oo	2
	12-24	1oo	2

Tobacco smoke was produced by a smoking machine (Filtrona). One or four cigarettes were continuous smoked with one puff of two seconds duration each minute with a volume of 35 ml in a total smoking period of ten minutes per cigarette. The cigarettes used had the following specifications: Length 85 mm, diameter 8 mm, filterlenght 2o mm, smoke nicotin 2,2 mg/cigarette and 27 mg tar/cigarette, tar defined as total particulate phase ÷ water and nicotin. Same cigarette brand was used in the experiments with individual smoking.

In order to obtain a homogenous aerosol, the room air was ventilated with two fans during all experiments. The following basic ventilation equations were therefore adaptable to be used for the gaseous contaminant phase, theoretically for each of the components in the complex mixture of various gases and vapours in the tobacco smoke.

$$c_t = \frac{q}{nV}(1 - e^{-nt}) + (c_o - c_y)e^{-nt} + c_y \qquad (1)$$

where

c_t = concentration of specific vapour component in room at any time (mg/m^3)
c_o = initial concentration of vapour in room (mg/m^3)
c_y = concentration of vapour in the infiltration air (mg/m^3)
t = time (hours)
V = volume of room (m^3)
q = quantity rate of generation within the room, the number of air changes per unit time (mg/h)
n = air change rate/h (dilution ventilation rate).

Equation (1) can be reduced as follows for the conditions $t \to \infty$ and $q = 0$

$$c_t = \frac{q}{nV} + c_y \quad .... \qquad (2)$$

and

$$c_t = (c_o - c_y)e^{-nt} + c_y \quad .... \qquad (3)$$

Meanwhile a certain amount of the vapour components in the smoke will be eliminated by adsorption to surfaces or change identity by chemical reactions. The result of this will be an elimination rate equivalent to a higher rate of dilution ventilation.

In the case of non-perfect mixing conditions in the room the equations can be modified by introducing a mixing factor m as shown by Turk. This simply indicate:

$$n_{eff.} = m \cdot n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

It is obvious that the emission given off from individual smoking and machine smoking will not be exactly the same. Not only will differences in inhalation rate means differences in combustion temperatures and changes in mainstream smoke, but retention of a certain part of the aerosol will take place in the airways and lungs of the smoker himself. In order to investigate those possible co-effects on the aerosol parameters under variable exposition conditions various smoking intensities and ventilation rates were combined in 16 experiments (table 1).

As a requisite alternative to make a total continuous recording of all components of the aerosol the following variables were determined indicating the main fractions of the smoke:

1) condensation nuclei (Gardner Ass.)
2) suspended particulate matter (TSI Particle Mass Monitor)
3) carbon monoxide (URAS II)
4) subjective voting of irritants and odours.

The ventilation rate in the climate chamber was monitored by gas meters and in addition controlled by elimination measurements of a gaseous radioactive tracer (Krypton 85). The air supplied was outdoor air filtered by an absolute filter and charcoal filter, effecting the background for all the airborne contaminants to be considered as close to zero as possible.

Results

The functions of condensation nuclei, total suspended matter and carbon monoxide were characteristically following the proceeding steps of each experiment:

First hour)	Pre-exposure period. Climate chamber occupied by operators of smoking machine or members of the smoking panel, but no smoking.
Second and third hour)	Smoking according to intended smoking intensity.
Fourth hour)	Lunch and no smoking in experiments with individual smoking.
Fifth and sixth hour)	Smoking continued.
Seventh hour)	End of smoking. Measurement of elimination rates.

Corresponding to these time intervals were found the no-smoking-background concentration, the increase during a constant emission rate, the steady state concentration and the washout function as resulted by the combined effect of the various elimination processes valid for the specific part of the aerosol.

It was found that in spite of the experimental arrangements maintained to assure complete mixing and a constant continuous emission, the concentrations all were fluctuating to a certain extent in all concentration phases during repeated dublications of experiments. This is shown on figures 1, 2 and 3 for each aerosol fraction measured during continuous smoking of one cigarette in the climate chamber and an air change rate of 4. The number of condensation nuclei varied from 90000-150000 per m^3, the SPM count from 350-500 $\mu g/m^3$ and carbon monoxide from 3.5-5.0 ppm. It was further shown, that the elimination rate of CO was equal to the ventilation rate, but the equivalent elimination rate for droplet nuclei was 1.5-2.o times, and for SPM 2-3 times more than the same value.

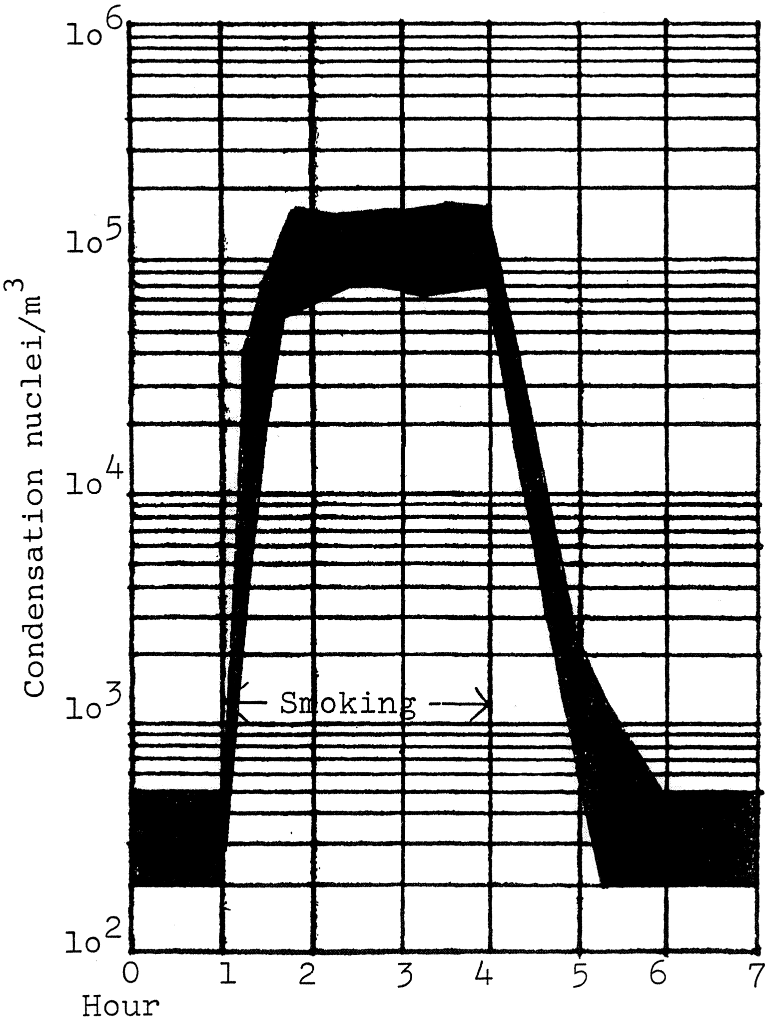

Figure 1. Condensation nuclei concentration measured during four repeated experiments at same exposure: 6 cigarettes/h in smoking hours, ventilation 200 m^3/h corresponding to 4 air changes/h in the climate chamber.

In the complete series of experiments it was found, that only in case of an air change rate higher than 8 times per hour the elimination rates were equalizing. This means that in order to avoid the impact of tobacco smoke on surfaces in a room, a supply of fresh air

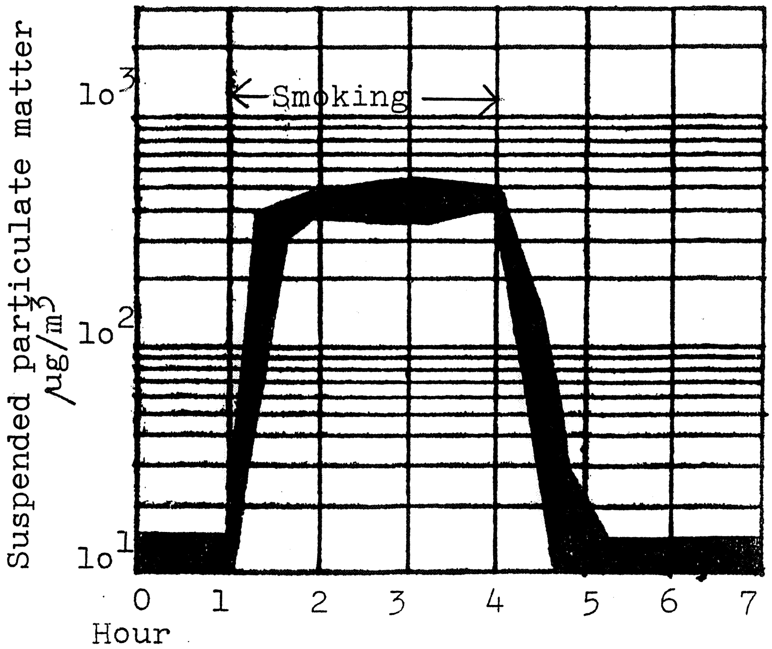

Figure 2. Suspended particulate matter measured during four repeated experiments at same exposure: 6 cigarettes/h in smoking hours, ventilation 2oo m^3/h corresponding to 4 air changes/h in the climate chamber.

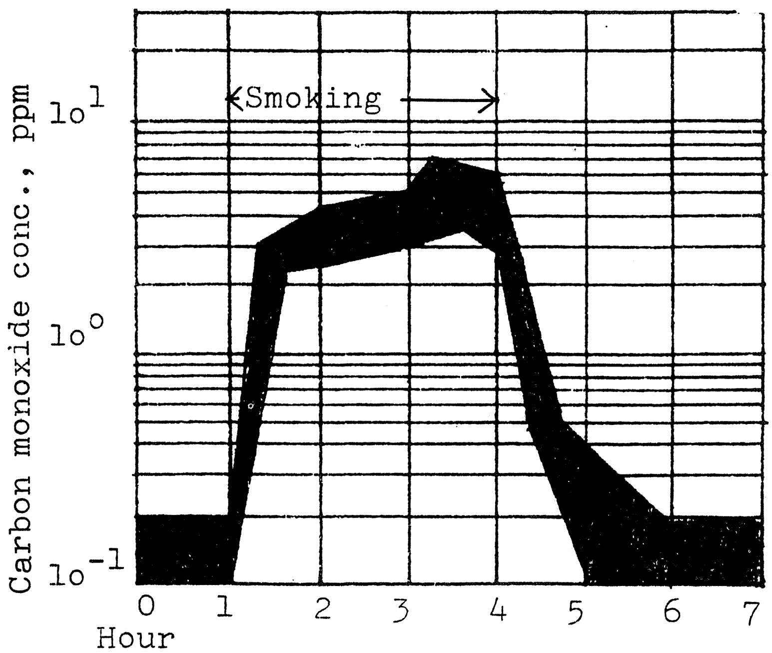

Figure 3. Carbon monoxide concentration measured during four repeated experiments at same exposure: 6 cigarettes/h in smoking hours, ventilation 2oo m^3/h corresponding to 4 air changes/h in the climate chamber.

for dilution should be of the magnitude of 6-7 m^3/min and cigarette smoked or 6o-7o m^3 of fresh air per cigarette smoked.

The relationships between ventilation rate and steady state concentration are shown in fig. 4, 5 and 6. Extrapolation of experimental data down to hypoventilation rates as prospected in some energy conservation procedures in housing indicates the harzardous concentrations possible to obtain under those conditions. It is obvious that tobacco smoke as well as the presence of other emission sources will create a definite health problem, when air change rates are below o.7, even at the lowest smoking rate of 6 cigarettes per hour performed in the experiments. This equals an air supply of appr. 6 m^3/cigarette smoked. It is even theoretically possible to exceed the TLV-values for occupational exposure at high smoking rates. Preventing this condition to occur will normally be the need for a relatively long exposure time necessary to build up the steady state concentration at low turn-over rates, but on the other hand may non-uniform mixing in a room be a fortifying factor for the exposure-inhalation dose relationship. The steady state concentrations obtained by individual smoking compared to these obtained by standardized machine smoking showed only a marked difference in the case of condensation nuclei, caused by the retention in lungs and airways of the smoker of mainstream smoke inhaled.

Opposite the total suspended particulate matter was a little higher by individual smoking. However, this could be due to common shedding of particles from skin, air and clothes from the smokers.

The results of the subjective voting on eye and nose irritation, odour intensity and odour pleasantness showed that odour intensity was increasing before irritation, and nose and throat irritation was occurring before eye irritation, but after eye irritation had started, it was given the highest score of irritation degree. The smokers did mostly vote the odour as neutral rather than pleasant or unpleasant. The individual variation voting was ab. ± 25% from the mean in scale points. Some individuals seemed clearly to be more sensitive to odours and irritation than others. In the population at large including non-smokers and hyper-sensitive subjects this would suddenly be much more marked. Determing minimum ventilation rates from this experimental data on subjective votes should therefore include considerations on precautionary measures.

Conclusion

This comment already anticipate some of the discussion and conclusion of the results. It has first and foremost been demonstrated that each component of the tobacco aerosol should be observed with regard to its own room air distribution and elimination.

A supply rate of ventilation of 6o-8o m^3/ cigarette smoked dependable of the volume and the surface characteristics of the room seems to be necessary to eliminate to tobacco smoke from the room before its adsorption in the room.

It is evident that such a ventilation rate will meet difficulties in the future caused by claims on energy conservation precautions. A need for further guidance for the design of low-ventilation rate housing related to the active as well as the passive smoking based on extended experiments seems to be obvious.

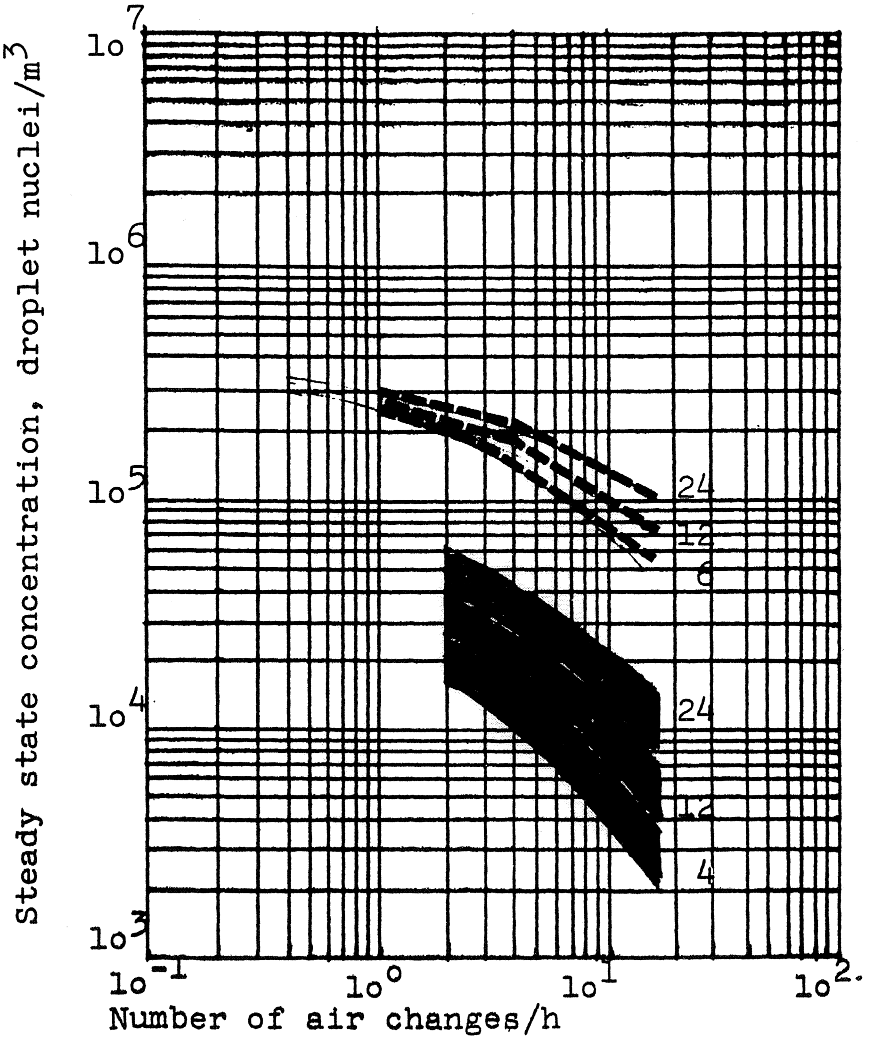

Figure 4. Steady state concentration of condensation nuclei at various ventilation rates with perfect mixing of room air for continuous smoking of 6, 12 and 24 cigarettes/h.
Upper curves: smoking machine experiments, lower curves: individual smoking.

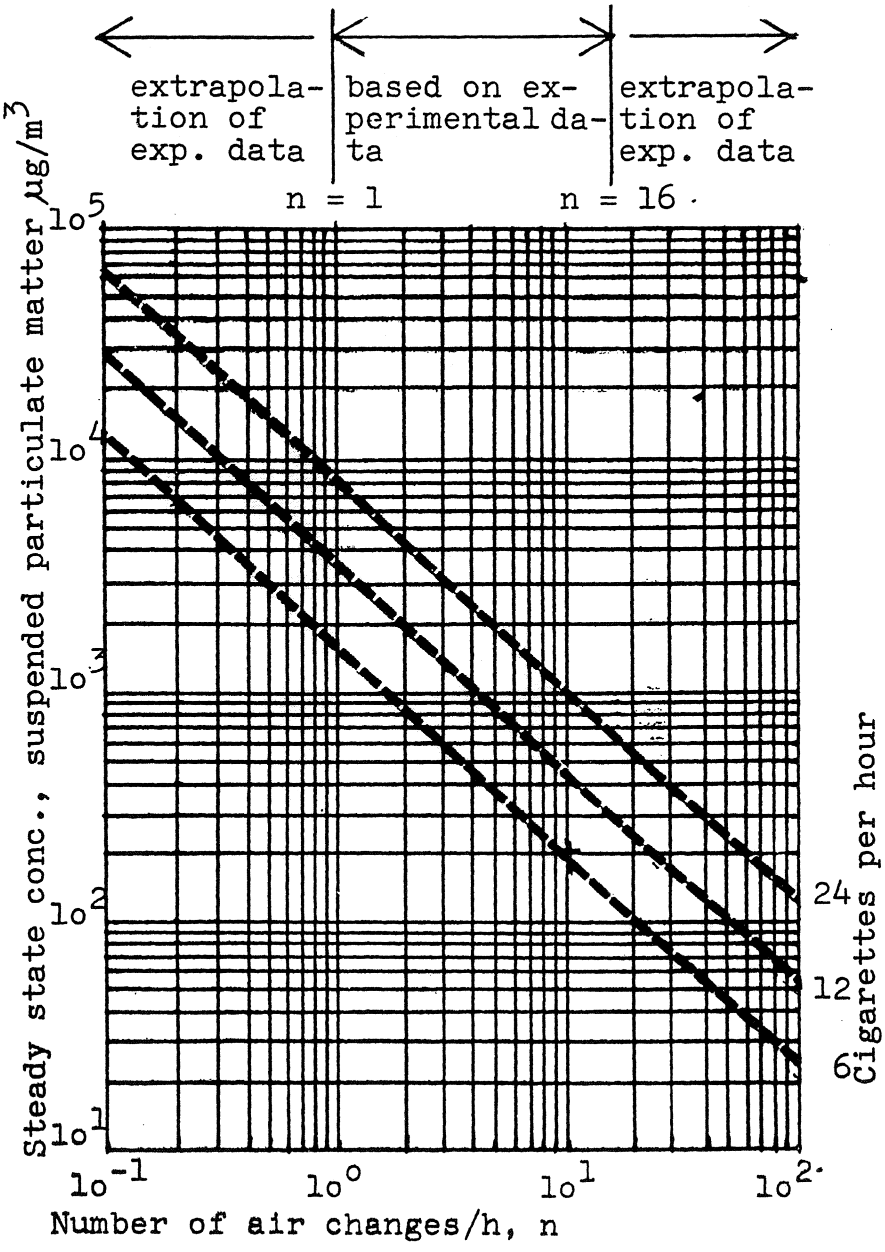

Figure 5. Steady state concentration of suspended particulate matter at various ventilation rates with perfect mixing of room air for continuous smoking of 6, 12 and 24 cigarettes/h.

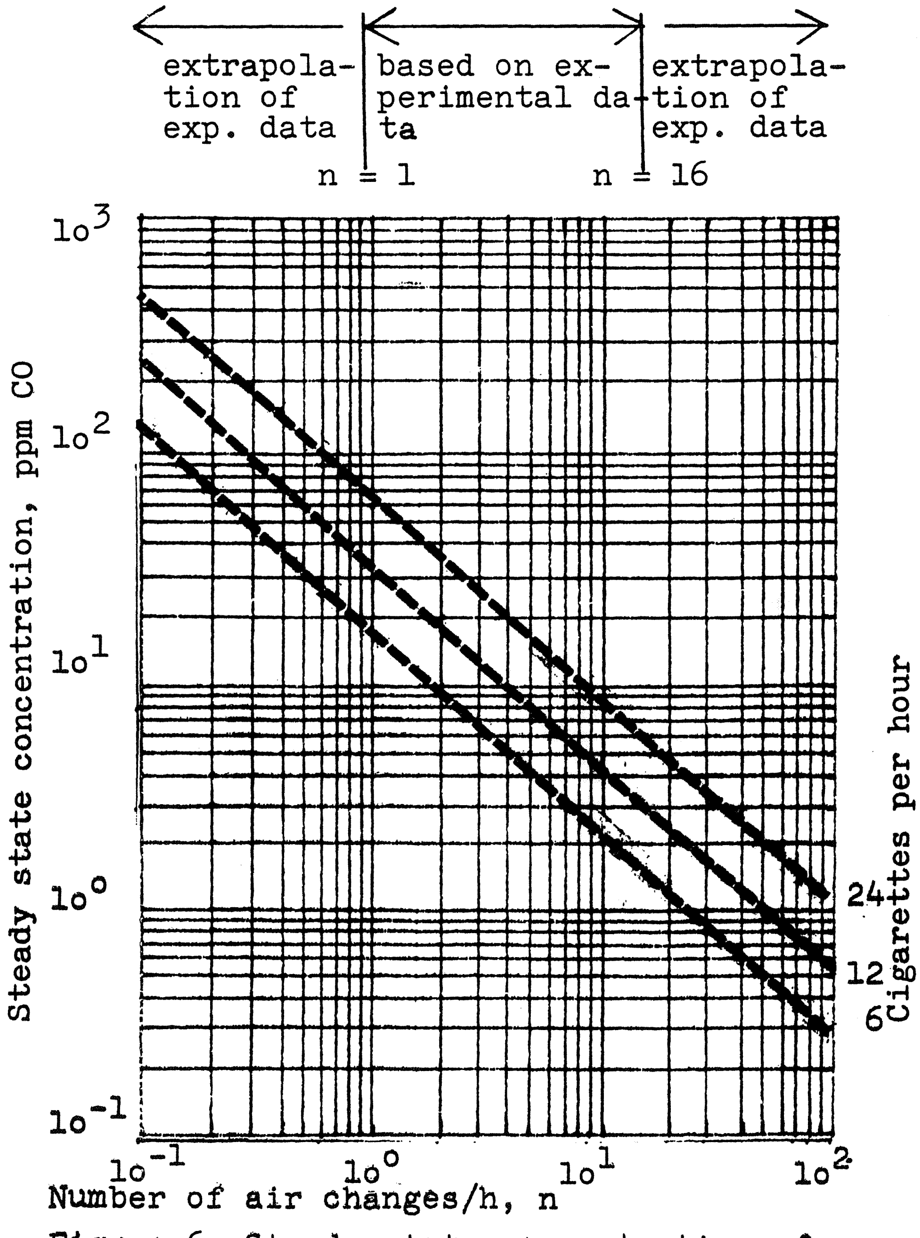

Figure 6. Steady state concentration of carbon monoxide at various ventilation rates with perfect mixing of room air for continuous smoking of 6, 12 and 24 cigarettes/h.

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DISCUSSION

H.U.Wanner
Inst. für Hygiene und Arbeitsphysiologie, CH

In a study about Air Pollution due to Tobacco Smoke Fischer et al. (Institute for Hygiene, Zurich) concluded that mean values of about 3 ppm CO and about 150 ppb NO (as indicators for tobacco smoke) caused irritations and annoyance (12 % of 360 guests indicated moderate to strong eye irritations). These effects should be considered for evaluating ventilation rates. Have you made similar observations?

G.R.Lundqvist

In the experiment, where four subjects were exposed to cigarette smoke equal to a CO-concentration of 3 ppm, all four subjects voted for distinct odour impression, and of the four one did not feel any irritation or annoyance, one had no eye irritation but weak to distinct irritation of the nose and throat, while two had periods of weak eye irritation in addition to weak to distinct irritation of the nasal-pharyngeal airways.

D.L.Swift
Johns Hopkins
School of Medicine,
USA

It is well known subjectively that smoking in a room causes retention of odours and particulates in carpets, curtains, fabric covered furniture, etc. What influence might the presence of these materials have on the ventilation requirements for CO and suspended particulates?

G.R.Lundqvist

CO is monitored as an indicator of the tobacco smoke, which is not influenced by adsorption in materials. Suspended particulate matter and certain vapours are temporarily eliminated from the air by retention on surfaces and may later be resuspended.

The view expressed in this paper is that ventilation rates should be sufficient to remove the smoke aerosol as soon after emission that adsórption only takes place fractionally. On the other hand, you could assert that the presence of adsorption surfaces should be considered as useful air cleaners in a smoky environment. But it is not comfortable to smell your own clothing after such an experience.

The test room used in this investigation with its aluminium surfaces gives very little guidance for the effect and magnitude of retention in ordinary living rooms.

P.O.Fanger
Technical University
of Denmark

You have found that 60-70 m^3 of fresh air per cigarette smoked are needed "to avoid the impact of tobacco smoke on surfaces". Why is it so important to avoid the impact of tobacco smoke on surfaces? I thought that it was much more important to avoid the impact of tobacco smoke on human beings, i.e. subjective irritation and discomfort caused by odor. Would it not be possible from your subjective votings to estimate the fresh air per cigarette required to avoid discomfort and odor complaints?

Why did you run your experiments at 65 % rh when it is well known that tobacco smoke is more irritating and the odor is perceived as stronger at the much lower humidities, occurring most often indoor during the winter season?

G.R.Lunqvist

As answer to the first question reference is made to the foregoing comment.

Discomfort and annoyance related to smoking intensities and ventilation rates should be measured, not only by the votings from a panel of smokers, but also by panels of non-smokers, among these hyper-sensitive subjects. This was not done in this study.

The choice of relative humidity was made to fulfil the standard conditions for smoking machines as used in the tobacco industry. I agree that future studies on subjective votes should include lower and more common humidities.

G.Brundrett
Electricity Council
Research Centre, UK

I understood that smokers inhaled and retained the bulk of the mainstream cigarette smoke (1). I was therefore surprised to see that your smokers produced a higher particulate concentration in the test chamber than the smoking machines. Did your smokers inhale in any special way?

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G.R. Lundqvist

It was shown that the steady state concentration obtained by individual smoking compared to those obtained by standardized machine smoking showed a marked difference in the case of condensation nuclei, caused by the retention in lungs and airways of the mainstream smoke inhaled. Our subjects were just supposed to breathe and inhale in the same special way they were used to.

When the total suspended particulate matter was a little higher in the climate chamber in the experiments with individual smoking than in the experiments with machine smoking in the non-occupied room, it could be explained by the shedding of particles from clothing and body surface from the subjects.

M.Rolloos
Delft University
of Technology, NL

A most important statement is missing in the conclusions of your paper, that is: reduce smoking!

G.R. Lundqvist

Thank you for the reminder. In the most common cases of inadequately ventilated rooms: I agree.