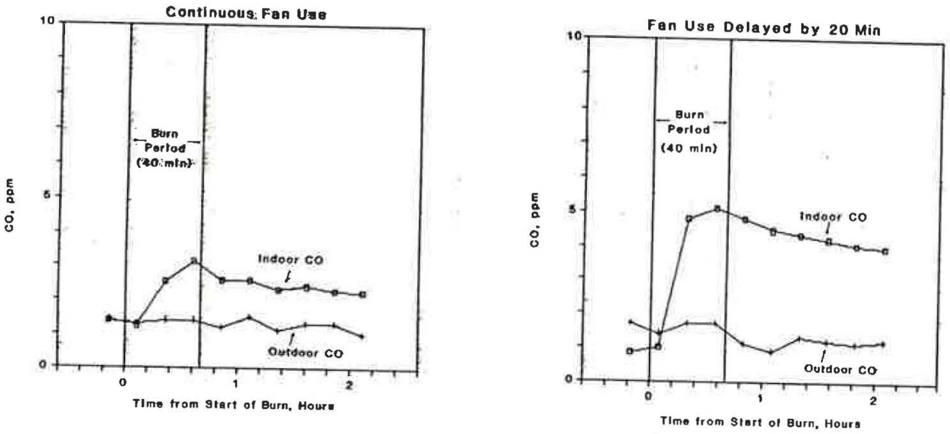

Figure 1: CO concentrations during simulated 40-minute cooking episodes--continuous versus delayed use of range hood fan

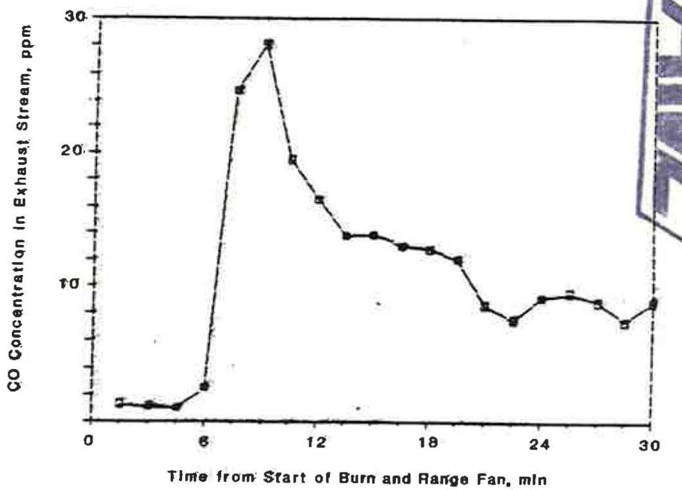

Figure 2: CO concentrations in the range-fan exhaust duct following ignition of a gas-fired burner and oven

TURBULENT AIR FLOW MEASUREMENTS IN VENTILATED SPACES

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Abstract

The purpose of the present study is to investigate the characteristics of turbulent air flow in the occupied zone of ventilated spaces: air velocity, standard deviation, turbulence intensity and fluctuation frequency. The study is accomplished by making field measurements in dwellings and offices with various ventilation and air distribution systems. Rooms with only most typical supply and exhaust devices were chosen to the study. In each space probes were placed at least at three locations in the occupied zone. At each location, measurements were performed at four heights: 0.05, 0.15, 1.1 and 1.7 m above the floor level. The relationship between the mean velocity and the standard deviation was calculated at every four heights. The instrumentation was designed and built in the laboratory of Heating, Ventilating and Air Conditioning of Helsinki University of Technology. In order to analyse fluctuation frequencies a computer program, that uses Fast Fourier Transform method, was developed. The paper will comprise the summary of results and discuss the influence of air distribution and ventilation system on the measured factors.

Introduction

Draught is one of the most common problems in ventilated spaces that causes complaints. According to the study of Fanger and Pedersen (1) the air velocity as well as the velocity fluctuation can cause discomfort. The fluctuation of air flow can be characterized by the mean velocity and the turbulence intensity. In addition to the fluctuation in itself the fluctuation frequency is also important. The discomfort has a maximum at frequencies around 0.3 - 0.5 Hz (1).

Thorshauge (2) measured velocity fluctuations in 12 different ventilated spaces with no or low thermal load. He found no predominant frequency in range 0.3 - 0.5 Hz. On the contrary practically all the energy lied in the interval 0 - 0.2 Hz. Hanzawa, Melikow and Fanger (2) investigated later the characteristics of turbulent air flow in 22 different ventilated spaces at different conditions. They observed that the turbulent energy was spread up to 10 Hz in dependence of the ventilated space.

Quite few experimental draught studies have altogether been reported in the literature. Therefore it is appropriate to investigate the characteristics of turbulent air flow by making field measurements in a wide range of spaces with various ventilation and air distribution systems.

Measuring method and equipment

The measurements were performed in spaces with various ventilation and air distribution systems and with most typical outlet and exhaust devices, Table 1. Measurements were made in summer conditions, cases 1 - 17 from Table 1, and in winter conditions ,cases 18 - 24 from Table 1, in the Helsinki area.

Table 1. Summary of characteristics of spaces investigated.

No. & Symbol	Type of the room	Ventilation or air distribution system	Floor area (m^2)	Nominal time constant (h)
1 ○	Office	Ceiling registers	19	0.3
2 ⏀	"	Wall registers	17	0.4
3 ◊	"	Mechanical exhaust with supply to hall	31	0.6
4 -○-	Meeting room	Wall registers	24	0.7
5 ⌖	Open plan office	Ceiling registers	450	
6 □	Office	Ceiling diffusers	17	
7 ▽	Studio	Holed ceiling	45	0.04
8 △	Office	Mechanical exhaust with supply to hall	17	0.5
9 ●⧫	Semidetached house	Natural	85	
10 ⌀	Office	Wall register	11	0.9
11 ⌀	"	- " -	25	
12 ⧫	Flat	Natural	25	0.9
13 ⊙	Office	Ceiling registers+ exhaust air windows	10	0.2
14 -●-	"	- " -	10	0.4
15 ✦	"	- " -	12	0.2
16 ■	"	- " -	11	0.3
17 ★×	Semidetached house	Floor diffusers	100	
18 ▼	Open plan office	Ceiling diffusers	425	0.6
19 ▲	- " -	- " -	425	
20 ●	Office	UNO-diffuser	16	
21 ■	Open plan office	UNO-diffusers	425	
22 ■	- " -	Ceiling diffusers	425	
23 ▷◁	Flat	Mechanical exhaust	82	0.6
24 ►◄	same as case 9, but in winter conditions		85	

In each space probes were placed at three vertical rods at following sites: 60 cm from the window-wall, into the middle of the room and 60 cm from the rear-wall. Furniture could of course change these figures. In every rod there were four probes at heights: 0.05, 0.15, 1.1 and 1.7 m above the floor level. Measurements were thus made at twelve points in each space. Exception of that were case 1, 24 points, and case 5, 72 points. Measurements at two heights near the floor were made to get a closer view at the behavior of the air flow on that level. During the measurements offices and dwellings were unoccupied, with the ventilation system operating normally, while in open-plan offices employees were working normally but of course not disturbing the measurements.

The instrumentation was designed and built in the laboratory of Heating, Ventilating and Air Conditioning of Helsinki University of Technology. It consists an anemometer, thermistor probes, four rods and a microcomputer. With the relay system air temperature and velocity from 128 different points can be measured in turn. The measuring system is all automatic. The probe is designed so that the output voltage is nearly independent on the direction of air movements: inaccuracy of the velocity is about ± 3 %, when air velocity is higher than 0.05 m/s. The time constant of the system is less than 1.0 second.

With this equipment, the air velocity was measured 5 times per second over a measuring period of 200 seconds in each point. Measurements were repeated generally 4 times at 1 hour intervals. Assumption that the air temperature doesn't change essentially during the velocity measurement is reasonable, when making the temperature compensation.The temperature and relative humidity of the space and outdoors were measured too. The volume flow, temperature and velocity of supply air were in most spaces measured. In order to analyse fluctuation frequencies a computer program, that uses Fast Fourier Transform method, was developed.

Results

By means of linear regression analysis, the relationship between mean velocity and standard deviation is shown in Table 2.

Table 2. Regression equations for standard deviation of the velocity as a function of the mean velocity for each of the four measuring levels. Regression equations for the field study of Hanzawa, Melikow and Fanger (2) and Thorshauge (3) are shown for comparison.

Measuring height m	Study	Regression equation m/s	Correlation coefficient	Number of values
1.7	(2) present	$\sigma = 0.266\bar{v} + 0.003$ $\sigma = 0.288\bar{v} + 0.007$	0.820 0.748	204
1.1	(2) (3) present	$\sigma = 0.328\bar{v} + 0.002$ $\sigma = 0.210\bar{v} + 0.040$ $\sigma = 0.283\bar{v} + 0.009$	0.837 0.940 0.756	14 188
0.15	present	$\sigma = 0.098\bar{v} + 0.022$	0.391	229
0.10	(2) (3)	$\sigma = 0.191\bar{v} + 0.008$ $\sigma = 0.130\bar{v} + 0.020$	0.668 0.600	28
0.05	present	$\sigma = 0.137\bar{v} + 0.015$	0.547	255

In Fig. 1, a percentage distribution of the mean velocity and turbulence intensity for all measurements is shown. As expected the turbulence intensity varied substantially. At heights of 1.7 m and 1.1 m about 90 percent of acceptable values varied around 25 - 50 %, at height of 15 cm the range was 20 - 45 % and at height of 5 cm the range was 15 - 40 %.

A frequency analysis of the velocity variations revealed that in the range 0.1 - 1.0 Hz there was no predominant frequency in the spectrum. The locations of frequency peaks were quite random between spectra calculated from velocity values of repetition measurements.

Discussion

The present study is accomplished by making more than 1300 velocity measurements in various spaces ventilated in different ways. About 870 velocity values were acceptable for the investigation since their mean value was more than 0.05 m/s. The regression equation near the floor (5 cm and 15 cm) in Table 2 agrees quite well with the regression equation of Hanzawa, Melikow and Fanger (2) and Thorshauge (3). The regression equation for head height of sitting person (1.1 m) in Table 2 passes nearly the zero point which denotes that the turbulence intensity as a function of the mean velocity varies less at the head height than near the floor. This phenomenon doesn't agree with the experiments of Thorshauge but fits well with the regression equation of Hanzawa, Melikow and Fanger.

Decreasing of the mean velocity and increasing of the turbulent intensity when the level from the floor increases is observed in Fig. 1. However in some spaces, cases 1, 4, 5, 14, 15, 16 and 18 from Table 1, the phenomenon is reversed.

Spaces with mechanical exhaust with supply to hall ,cases 3 and 8 from Table 1, differed obviously from other cases: the air flow at heights 1.1 m and 1.7 m was nearly laminar with low mean velocity, while near the floor level the air flow was turbulent with slightly higher mean velocity.

The frequency analysis of the velocity variations revealed that the frequency peaks were highest in the beginning of the spectrum. It is likely a character of the Fourier Transform when velocity data to be transformed is not periodical. The energy level of the spectrum seems to depend on the mean value of velocity measurement. The higher is the mean velocity, the higher is the energy level. Because no predominant frequency in spectrums investigated was found, it seems that in ventilated spaces the air flow in the occupied zone is fluctuating randomly.

Summary

Air temperature and velocity measurements were performed in the occupied zone of 23 typically ventilated spaces. A linear relationship between mean velocity and standard deviation was found at every height investigated. The turbulence intensity varied at heights of 1.7 m and 1.1 m above floor level around 25 - 50 %, at height of 15 cm around 20 - 45 % and at height of 5 cm around 15 - 40 %. No predominant frequency in the range 0.1 - 1.0 Hz of spectra investigated was found.

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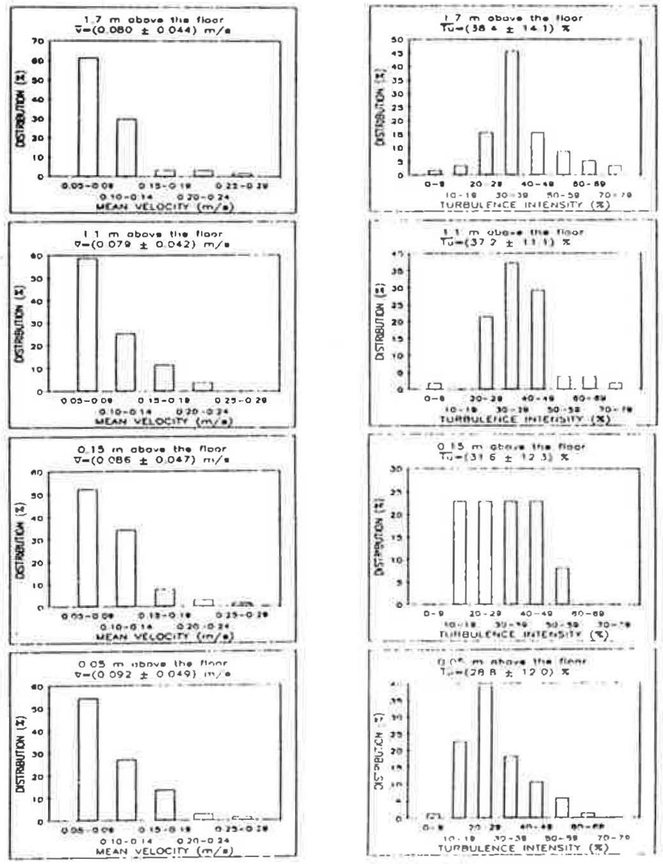

Fig. 1. A percentage distribution of the mean velocity and turbulence intensity at different heights.