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LABORATORY TESTS AND FIELD MEASUREMENTS OF AIR VELOCITIES AND TEMPERATURE GRADIENTS IN RESIDENTIAL BUILDINGS

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SUMMARY

The study focuses on the development of ventilation systems for residential buildings, which will provide a good thermal climate and a good air quality without being too complicated.

In full-scale laboratory tests, nine different alternative ways to ventilate a room (with different supply air and exhaust air solutions) were studied. Field measurements were carried out at different outdoor temperatures and at different air flows. The experimental procedure was to increase the airflow through the supply devices until draught or temperature gradients became unacceptable.

The laboratory tests indicated that if the room was not supplied with preheated outdoor air, it was difficult to keep the air velocities and the temperature gradients at acceptable levels at air flow rates corresponding to more than 0.5 air changes per hour. When the room was supplied with preheated outdoor air, no problems appeared at air flow rates corresponding to up to 1.0 air changes per hour . A prerequisite for avoiding high air velocities is that the air supply devices are designed and located correctly.

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INTRODUCTION

Much attention is currently focused on the quality of the air in buildings. There are good reasons for this. New buildings are often more airtight than old ones. This can result in poor ventilation and poor air quality if measures to improve ventilation are not taken. Some building materials seem to emit gases and particles to such an extent that the quality of the indoor air is deteriorated. Moreover, buildings are now better insulated than they were earlier. If the improved insulation technique is incorrectly applied, problems with mould can occur and the air quality can be negatively influenced.

There is an on-going discussions about what rates of outdoor air flows have to be guaranteed in different types of buildings at different types of activities. The development of new standards and codes will probably increase the demands on ventilation air flow rates.

Residential buildings are often equipped with ventilation systems that are quite uncomplicated. A common solution is an exhaust system. However, with such a system the air flow rates are limited. An experience is that there is an obvious risk of draught and uncomfortable temperature distribution when the air flow rates exceed 0.5 air changes per hour. If higher air flows are needed the supply air must be preheated, i.e. more or less advanced supply air systems have to be installed.

It is important that possible demands on higher air flow rates in residential buildings do not lead to a deteriorated thermal indoor climate. This is the basis for the study of air velocities and temperature gradients in residential buildings reported in this paper.

The aim of the study was to find the upper possible limit of the air flow rates that does not cause discomfort, using different types of ventilation systems and supply air devices.

The study includes laboratory tests as well as field measurements, the latter of which will be complemented later. The field measurements and laboratory tests have, in most cases, been carried out under similar conditions, so that the results can be compared. For some of the supply air devices, results from previous laboratory tests are available [1, 2].

According to Swedish building standards, the supply air flow rate should be 4 l/s per person in a bedroom. However, nothing is stated as to the flows needed due to the emission from building materials in apartments.

The choices of ventilation systems have primarily been made on the basis of existing ventilation systems, installed in housing owned by one of the large housing companies in Gothenburg (Bostads AB Poseidon). The choice was later complemented with other solutions. It should be noted that the study does not include warm air systems.

THE REFERENCE APARTMENT

After studying the existing housing, it was considered relevant to choose an apartment type which was relatively common and had the desired type of ventilation. As the study was primarily aimed at bedrooms, the choice fell on a two-roomed apartment, with kitchen and bathroom, measuring 52 m^2. The apartment was supplied with fresh air via air slot devices in the bedroom and living room, located above the windows. In the bedroom, the device was placed 2 m above floor level, directly above the window. The exhaust air was extracted via the bathroom and kitchen. The air from the bedroom was extracted through an air slot over the bedroom door. The radiators were located below the windows in the bedroom and living room and were of the single row type suitable for low temperature systems (55°C/45°C). The windows were triple-glazed and the window sills inset into the wall. The dimension of the bedroom was 4 x 2.65 x 2.5m (length, breadth, height). An apartment of this type was regarded as a reference apartment when building the full-scale model. The majority of apartments used in field measurements were also of this kind.

LABORATORY TEST PROCEDURE

The full-scale model was constructed by using the bedroom of the reference apartment as a basis (figure 1). A large cooling wall was used to simulate the surface temperature of the windows. The temperature of the wall was changed in laboratory tests so that it agreed with the calculated surface temperatures of the window at the different outside temperatures studied. The temperature of the supply water to the radiator varied according to the existing supply water curve of the control system. Three of the walls were built of wood fibre board on wooden frames. The fourth wall faced a room which had triple glazing. In that room, the air movements could be studied without disturbing the air flow patterns in the full-scale room.

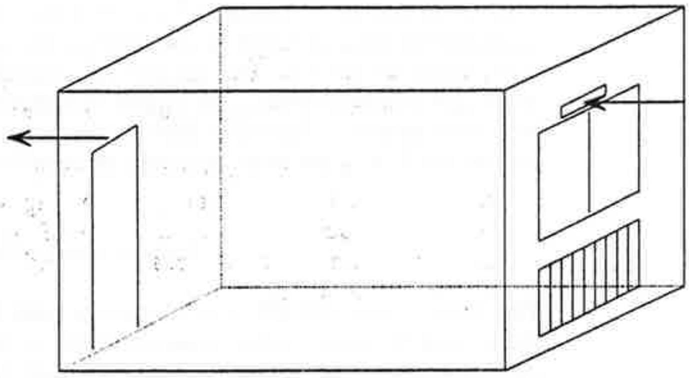

Fig. 1. Full-scale test room

Location of Sensors

Air velocities and temperatures were measured in 54 different positions in the room. 48 of these positions were placed in a grid, whilst the remaining six were moved around in the room to the selected positions, where the comfort criteria were most difficult to fulfil. The 48 sensors were placed at heights of 0.1, 1.1 and 1.7 m, respectively, above floor level. It should be pointed out that the measuring zone is only a part of the area normally occupied in a residential building. Note also that the sensors, see figure 2, nearest to the inlet device have been moved, so that they are positioned directly in front of the device.

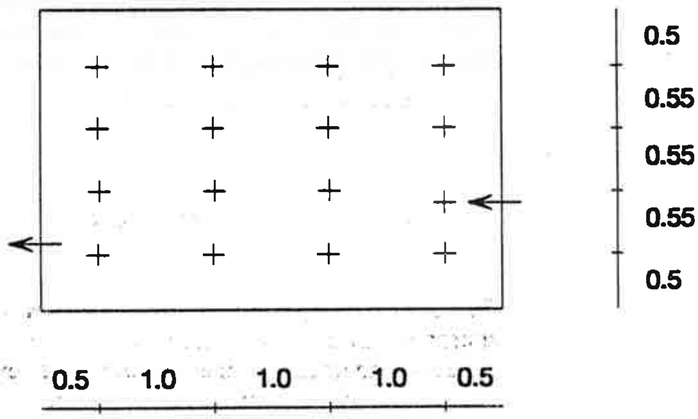

Fig. 2. Location of the 48 sensors placed at levels of 0.1, 1.1 and 1.7 m above floor level. The arrows show where the air slot device and the door are situated.

The surface temperatures of the windows were measured by thermocouples on each side of the window. The surface temperatures of the walls were measured at a centre point of each wall. As the cooling wall was large, this resulted in a certain amount of cooling to the outer wall. The inlet temperature of the supply air was measured by three or more thermocouples, the position of which varied according to the different devices. The exhaust air temperature was measured in the air slot above the bedroom door. The supply temperature of the radiator was measured by double sensors. The water flow to the radiator was measured by a rotameter, and the air flow to the room by means of an orifice.

Measurement system

The temperature and air velocity sensors were mounted on measuring poles and the measured values were transmitted via a data logger to a computer. The thermocouples were of copper-constantan and the air velocity sensors were of the hot-wire type. The direction of the sensors was determined by a smoke test. The smoke tests were performed separately for each sensor or, alternatively, by injecting smoke directly into the air duct. Each measurement cycle took 3 minutes and during this time, the following information was stored:

10 values from each air velocity sensor
5 values from each air temperature sensor
2 values from each surface temperature sensor
2 values of the supply air flow
2 values of the supply and return water temperatures of the radiator from each sensor

Both mechanical exhaust systems and balanced ventilation systems were studied. The choice was made, primarily bearing in mind the solutions which exist today in the apartment blocks belonging to the company mentioned earlier. This choice was then complemented with other alternatives. A total of 9 standard solutions were tested. The following choices of air devices were made.

Type of system	Name of Device	Location	Remarks
Mech. exhaust ventilation.			
Air slot terminal device	Fresh 31	Above window	Reference
	Fresh 31	Below window	
	Fresh 35	Above window	
Poppet device	Fresh 99		
Radiator device	Farex ENQ	Behind radiator	
	Sefovent Sefomix	Behind radiator	
Balanced ventilation			
	Fläkt CTVK-10	Above door	
	Fläkt CTF	Above door	e.g. for offices
	Farex EIV-80	Above door	

Table. 1. Choice of air devices

Supply air flows

As the aim has been to determine the maximum air flow that can be supplied via the various supply devices, the flows were gradually increased until problems with high air velocities (0.15 - 0.20 m/s), or large temperature differences arose (> 3°C between 0.1m and 1.7m above floor level). Generally, the air velocities caused problems before excessive temperature gradients arose. According to Swedish building standards, the flows of outdoor air should be 8 l/s in a bedroom for two persons.

Inlet temperatures

The basis for the choice of supply air temperature has been the climatic conditions prevailing for residential buildings situated in the Gothenburg area. The following supply air temperatures (for the mechanical exhaust systems) were considered interesting:

-15/-10°C winter case (corresponds approximately to the lowest temperatures in Gothenburg).

0°C spring/autumn case (the temperature in Gothenburg ranges between -5°C and +5°C during one-third of the year).

10°C cool summer case (the temperature in Gothenburg ranges between +5°C and +15°C during two-fifths of the year).

Note that a certain amount of pre-heating occurs via the supply devices.

Balanced ventilation systems were studied at an outdoor temperature of 0°C with the following inlet temperatures in the supply air.

* isotherm case
* $\Delta t = 5°C$ (5°C below room temperature)
* $\Delta t = 10°C$ (10°C below room temperature)

RESULTS FROM LABORATORY TESTS

The results presented here are based on a selection of three different devices, namely, an air slot device (reference device), a radiator device and a device for balanced ventilation. The air velocity sensors are calibrated to measure between 10 and 35 cm/s. Thus, no figures are shown for speeds exceeding 40 cm/s. Furthermore, the stated air speeds of less than 10 cm/s are considered uncertain due to self-convection from the hot wire sensors. In addition, only measurements for the critical sections are shown here, where the six extra velocity and temperature sensors were placed at relative intervals of 10-20 cm.

Air slot terminal device

Laboratory tests show high maximum air velocities when the air slot terminal device was located above the window. From figures 3a-c (Fresh 31), we can see that not even 4 l/s can be supplied through the device without the air velocity becoming too high at a vertical section 0.6 m in front of the outdoor wall. Air velocities lower than 4 l/s were not investigated, bearing in mind the recommendations prevailing for bedrooms. The greatest differences in temperature were less than 3°C between the highest and lowest air temperatures in the measurement section containing the six extra sensors. It should be noted that it is difficult to accurately measure the temperature in the air stream, as the cold air stream entrains warm air from the room.

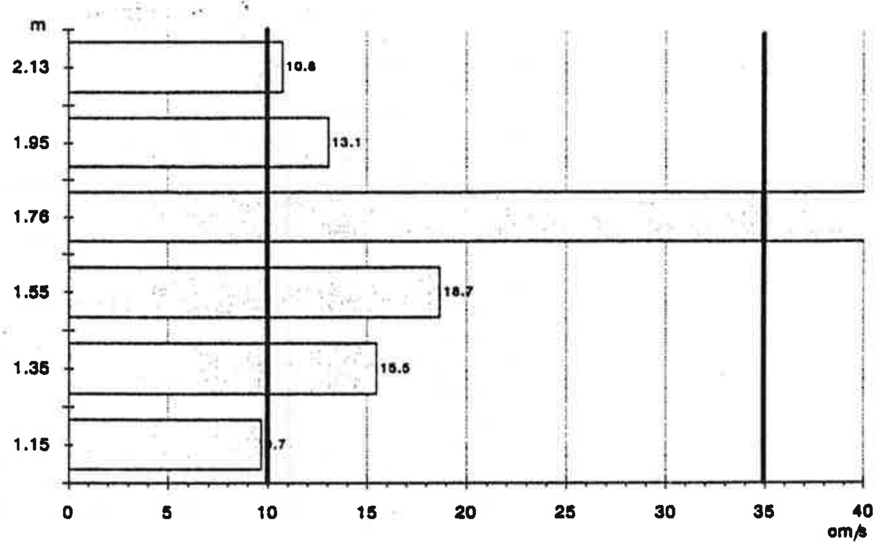

Fig. 3a. Vertical velocity profile for 4 l/s at an outdoor temperature of -12°C.

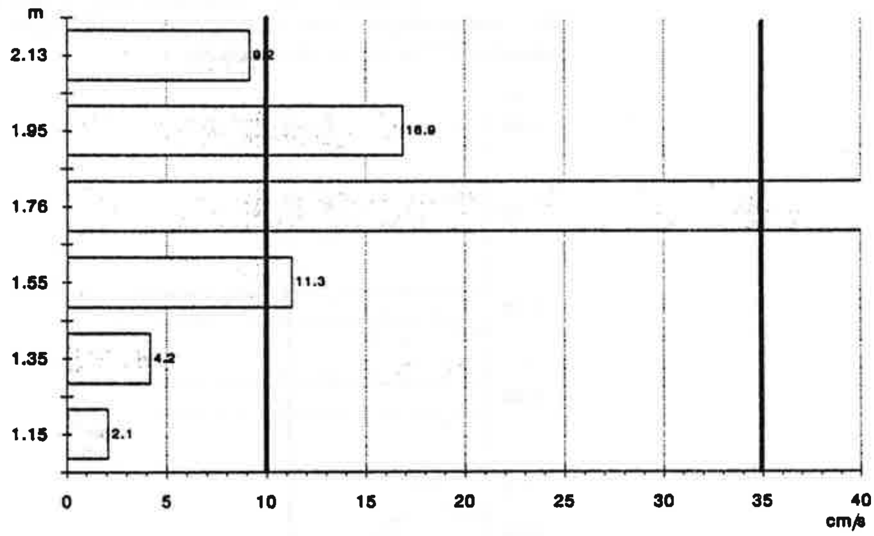

Fig. 3b. Vertical velocity profile for 4 l/s at an outdoor temperature of 0°C.

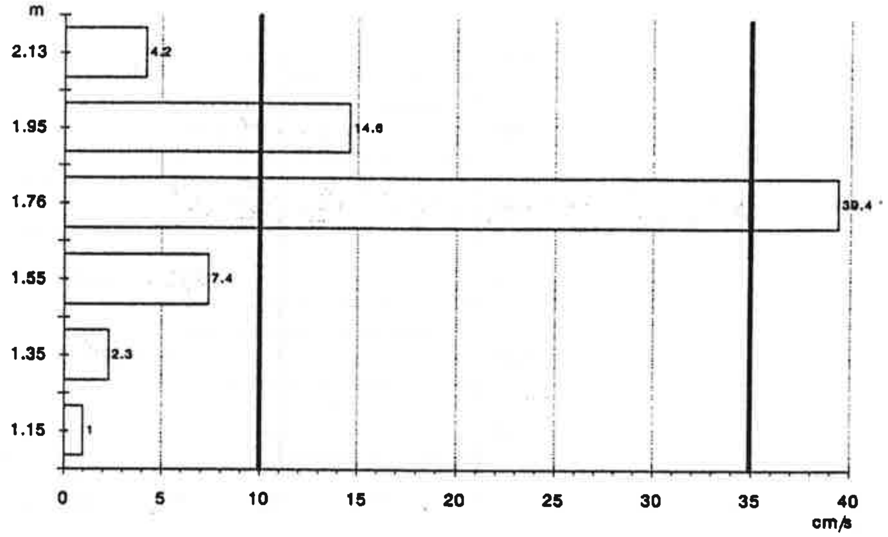

Fig. 3c. Vertical velocity profile for 4 l/s at an outdoor temperature of 10°C.

By placing the air slot device below the window, a lower velocity was achieved , but the air stream reached the occupied area at a very awkward height. At the lowest inlet temperatures, the temperature differences in the measurement section exceeded 3°C at an air flow of 6 l/s.

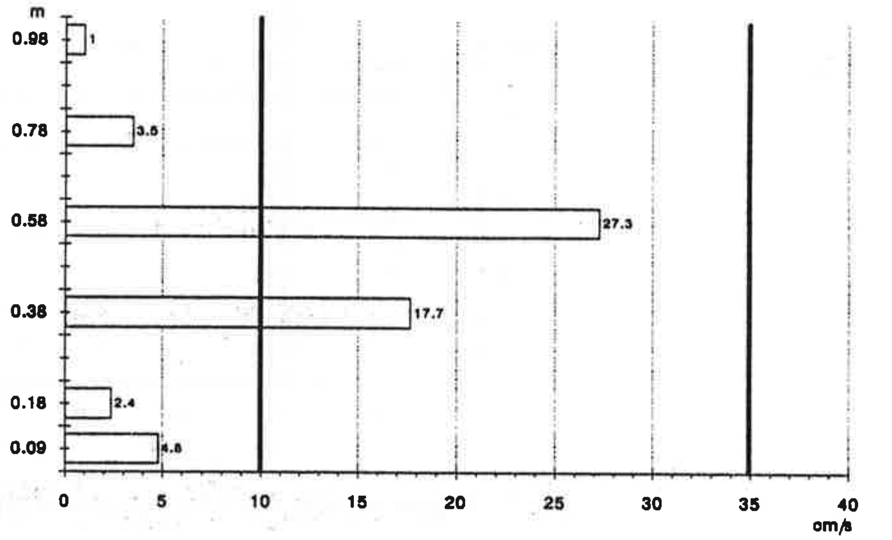

Fig. 4. Vertical velocity profile for the location of the slot terminal device below a window at 4 l/s and at an outdoor temperature of 0°C·

Radiator device

The radiator device showed no problematic velocities higher than 15 cm/s with an air flow of up to approx. 10 l/s. For higher supply flows, one type of device showed velocities somewhat higher than 15 cm/s at 0.1 m above the floor. Subsequently, the temperature gradient increased due to the fact that the air at floor level became cooler.

Balanced ventilation

The air was supplied via a device placed above the inner doors. The interesting section here was the head height of 1.7 m above the floor. The measuring points varied depending on the different air throws which the various devices gave for different cases (inlet temperatures and air flows). Devices with adjustable air throws were set at suitable angles. The limit for the acceptable air velocity was an air flow corresponding approx. to 10 - 15 l/s via the device. Figures 5a-b show velocity measurements for devices of type CTVK. At an inlet temperature of 5°C below room temperature, the temperature difference between different measuring points was only of the order of a tenth of a degree.

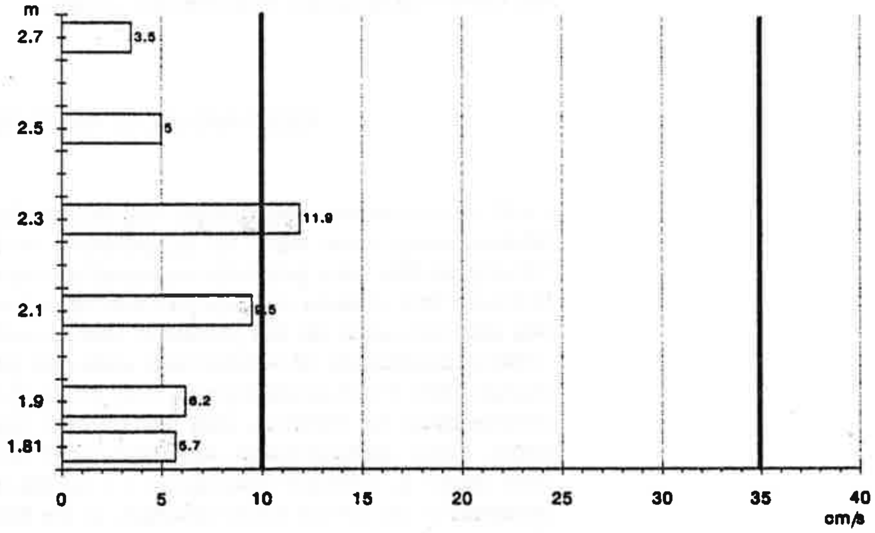

Fig. 5a. Horizontal velocity profile for a balanced system at an inlet temperature of 5°C below room temperature and an air flow of 12 l/s. The values of the Y-axis are the horizontal distances from the inlet device.

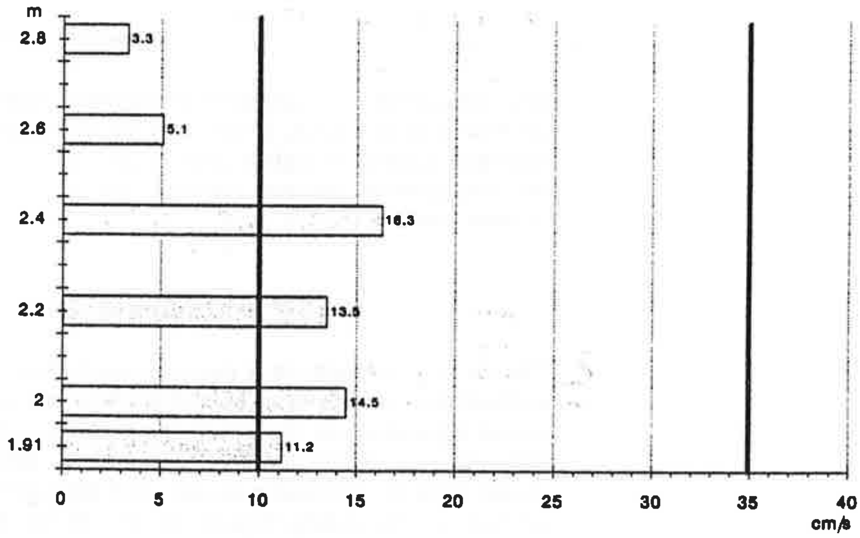

Fig. 5b. Horizontal velocity profile for a balanced system at an inlet temperature of 5°C below room temperature and an air flow of 15 l/s. The values of the Y-axis are the horizontal distances from the inlet device.

FIELD MEASUREMENT PROCEDURE

Field measurements were performed during the winter season in Gothenburg. Measurements were made for temperatures in the range of -8°C to +6°C. The velocity profiles were primarily measured in a vertical section 0.6 m from the outer bedroom wall. Besides air velocities and air temperature, the radiator temperature was also measured (in this particular case as surface temperature) as well as the surface temperature of window and walls, the plane radiant temperature and air change rates. Field measurements were primarily made in apartments with air slot devices above the windows. Only part of these measurements are presented in this paper. Other measurements were also made of radiator devices. Measurements were made in different apartments but as the main problem occurred in close proximity of the device, small variations in the dimensions of the bedrooms may be disregarded.

Location of the sensor

As has been mentioned earlier, the measurements were primarily made in the bedroom at a distance of 0.6 m from the window wall. To get a total view of the whole apartment, the air flows through all devices were measured in the apartment and the air change rate was also measured under different conditions. As the field equipment is limited to one measuring point at a time, the velocity profile was determined point by point. The relative distance between the measuring points varied depending on the outcome of the velocity measurements and the smoke test. Laboratory tests had shown that air velocities are a much greater problem than air temperature. The air temperature was therefore only measured close to the velocity maximum .

Measurement system

To measure air temperature, air velocities, relative humidity, surface temperatures and plane radiant temperatures, a portable climate analyzer (Brüel & Kjær Climate Analyzer type 1213) connected to a PC was used. Instantaneous values and average values were measured or calculated (3 minutes or longer). Air change rates were measured according to the decay method. N_2O was used as tracer gas measured by an infrared gas analyzer (Miran 101). The air flows were measured by a hot-wire anemometer (Swema 230).

Air flows and outdoor temperatures

In order to vary the flow of air through the devices, measurements were made partly using devices in original condition and partly cleaned devices or new ones. Furthermore, an increase in air flow was accomplished by forcing the air flow through the kitchen hood. To obtain an idea of the rate of unintentional ventilation, tracer gas measurements were made. The air flows through the bedroom air slot device varied from 1.7 l/s to 7.6 l/s during these measurements. In order to obtain values at different supply air temperatures, the field measurements were made on different occasions, which meant that the same apartment could not be used.

RESULTS FROM FIELD MEASUREMENTS

The air change rate measured in the bedroom was lower than the average rate for the whole apartment. All the doors were closed and all the air slot devices were open during the measurements. In this case it should be mentioned that the number of apartments studied were few, but the result is consistent with previous studies [3]. When the bedroom door was open and all other doors closed, the air change rate in the bedroom increased to the average value, or higher, compared to the rest of the apartment. Measurements were also made with the ventilation shut down, as well as with the air slot device closed in the bedroom.

Large differences in air flows could be measured between new devices and existing ones. In one case, the air change rate in the bedroom was doubled when the exhaust air devices in the bathroom and kitchen were changed for new ones. (0.34 to 0.66 air changes per hour). The highest air change rates (1.2) in the bedroom were obtained when the flow was forced into the kitchen hood. These measurements were made in calm weather conditions. Using new devices, the air change rate was also measured in windy weather, and the rate was increased to 0.96 air changes per hour in the bedroom at normal running conditions. All measurements were made when the temperature was a few degrees below 0°C. It was established that the air flow rate through the air slot devices was strongly influenced by the degree of dirt in the device. In another apartment, the supply air flow increased from 5 l/s through the air slot device in the bedroom to 7 l/s when a new air slot device was installed.

The ratio between the flow through the air slot device and the total air flow to the bedroom was 2/3 at normal running conditions.

The plane radiant temperature was measured in the middle of the room. No excessive surface temperatures on walls, floors or ceiling were found. The difference in temperature between the outer walls and the room air was always less than 1°C.

The velocity measurements show that the air flows exceeding 3.5 l/s led to unacceptable velocities in the room, see figures 6-8. The height, at which the air stream occurs, depends to a large extent on the inlet temperature together with the way in which the convection flow from the radiator affects the air stream. The radiator was set at maximum effect the whole time, and the supply water temperature was measured. At floor level, the air movements were usually directed towards the outer wall.

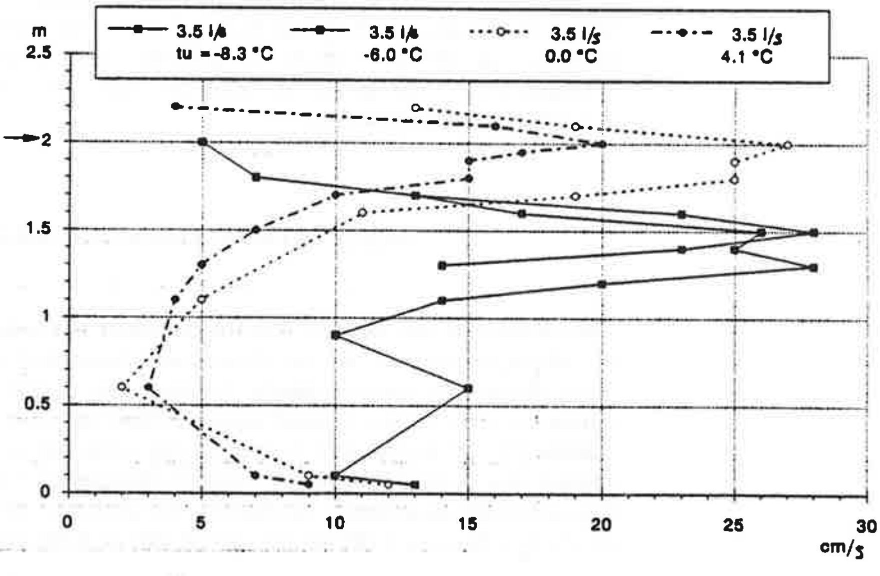

Fig. 6. Velocity profiles at 3.5 l/s at different outdoor temperatures (tu)

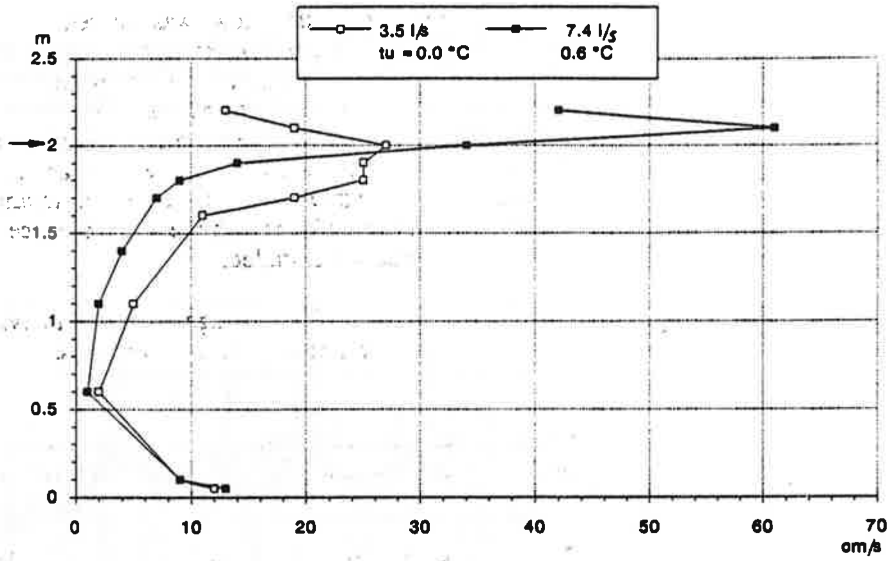

Fig. 7. Velocity profiles at an outdoor temperature (tu) of approximately 0°C.

The values given are based on 3-minute average values. Generally, the velocity is lower further away from the air slot device. When the air slot device is placed above head height and, thereby outside the occupied area, it is interesting to study the maximum air velocity in the occupied area. Figure 8 shows the horizontal velocity profile at 1.7 m above floor level at a supply air flow of 3.5 l/s and an outdoor temperature of 0°C.

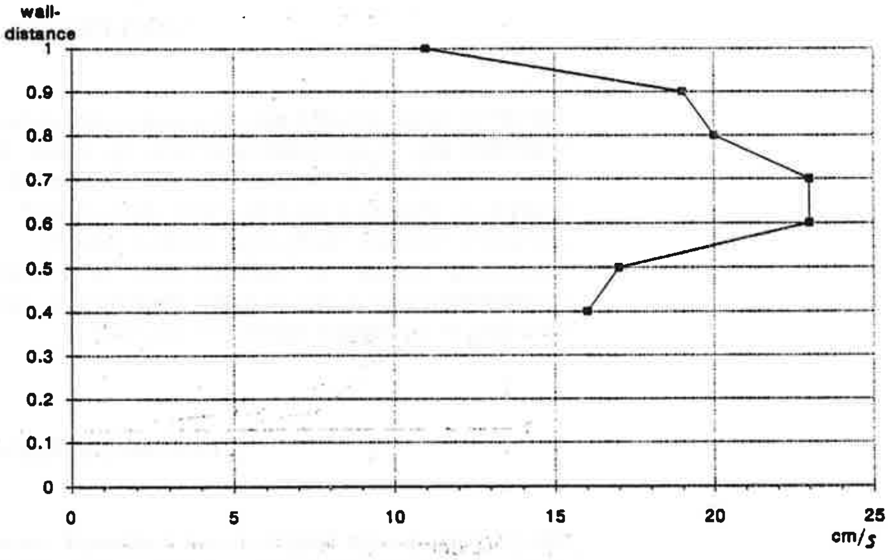

Fig. 8. Horizontal velocity profile at 1.7 m above floor level.

Also, the fluctuation of the air velocity has a great influence on the thermal comfort. Figure 9 shows the difference between instantaneous values and continuous 3-minute average values. The measurements were made at 1.3 m above the floor, at a supply air flow of 3.5 l/s and an outdoor temperature of -6.5°C.

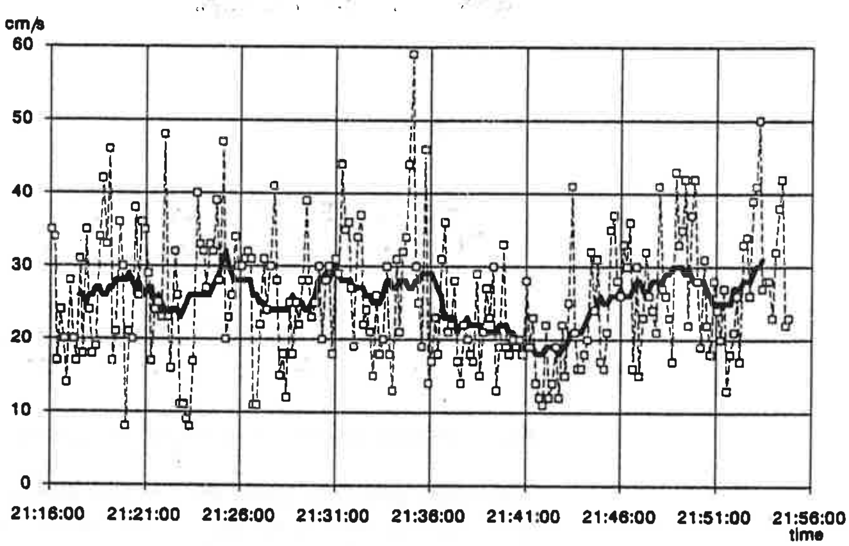

Fig. 9. Variation in velocity given as 3-minute average values and instantaneous values.

CONCLUSIONS

The field measurements and laboratory tests show a clear connection between air velocities and temperature gradients, in which the latter often are small. The reference air slot device does not fulfil the Swedish requirements for supply air to bedrooms. Balanced systems meet the demands but require extra duct systems compared with the mechanical exhaust systems. A reasonably simple system with preheating behind the radiator may be a good solution, but it should be remembered that a low radiator temperature can cause problems. The radiator has, thus, an important function in this case.

FUTURE STUDIES

The laboratory tests have included a series of more than 200 measurements, each containing about 800 measured values that will be processed further. With the reference air slot device, experiments have been made in a furnished room, with or without thermal load. Tests have also been made using diffuse ventilation with supply of air over a large area.

The field measurements will be complemented and the investigation will later also deal with the system solutions as well as maintenance and operation of ventilation systems in residential buildings.

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