Air Distribution Systems

Room Air Movement and Ventilation Effectiveness

Nielsen, Peter V.

Publication date:
1992

Document Version
Publisher's PDF, also known as Version of record

INSTITUTTET FOR BYGNINGSTEKNIK
DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITETSCENTER • AUC • AALBORG • DANMARK

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 25

Internat. Symposium on Room Air Convection and Ventilation Effectiveness, ISRACVE, Tokyo, Japan, July 1992

P. V. NIELSEN

AIR DISTRIBUTION SYSTEMS - ROOM AIR MOVEMENT AND VENTILATION EFFECTIVENESS

JULY 1992

ISSN 0902-7513 R9250

INSTITUTTET FOR BYGNINGSTEKNIK
DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITETSCENTER • AUC • AALBORG • DANMARK

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 25

Internat. Symposium on Room Air Convection and Ventilation Effectiveness,
ISRACVE, Tokyo, Japan, July 1992

P. V. NIELSEN
AIR DISTRIBUTION SYSTEMS - ROOM AIR MOVEMENT AND VENTILATION EFFECTIVENESS
JULY 1992 ISSN 0902-7513 R9250

Correction to: Air Distribution Systems - Room Air Movement and Ventilation Effectiveness (Indoor Environmental Technology Paper No. 25).

Page	It says	Should be
12	$14 \cdot 10^{-6}$	$14 \cdot 10^{6}$
14	$0.5\ (T_R - T_o)$	$0.5(T_R + T_o)$
17	T_{∞}-T_o when T_{∞} is	T_{∞}-T_o where T_{∞} is

International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

AIR DISTRIBUTION SYSTEMS - ROOM AIR MOVEMENT AND VENTILATION EFFECTIVENESS

Professor Peter V. Nielsen
Aalborg University
Denmark

ABSTRACT

Ventilation effectiveness is strongly dependent on room air movement and contaminant source location. It is shown that there exist gradients in contaminant distribution in the room in case of mixing ventilation and this will give rise to effectiveness different from 1.0. It is also shown that the location of the return openings may be very important compared with the small influence this location has on the velocity distribution in the room.

The air flow rate in a room is often at a level where low turbulence effect takes place and the ventilation effectiveness and the velocity distribution are strongly influenced by this effect.

It is shown how the temperature gradient and the temperature effectiveness are dependent on the location and type of heat sources in displacement ventilation. Concentration distribution and ventilation effectiveness are studied in a room with both stationary sources and movable sources.

The paper shows a description of the flow from a low level diffuser which is suitable for a design procedure in displacement ventilation.

KEY WORDS Mixing Ventilation, Displacement Ventilation, Ventilation Effectiveness, Temperature Effectiveness, Velocity in Occupied Zone, Vertical Gradient.

INTRODUCTION

A large number of experiments with air distribution systems have been made at Aalborg University during the years. This paper will be a review of some of the experiments from the last five years.

- Ventilation Effectiveness

- Displacement Ventilation

and

- Computational Fluid Dynamics

are the big issue in room air distribution at the moment.

The paper will discuss the ventilation effectiveness directly in some of the described experiments, or indirectly in other experiments with concentration gradients and temperature gradients. Displacement ventilation will be covered by the discussion of a number of experiments showing both vertical gradients and velocity distribution in the occupied zone. Experiments are very important in connection with the development of Computational Fluid Dynamics. The experiments in this paper show processes which are influenced by low turbulent effects and therefore difficult to predict by a numerical method. The experiments do also define the situations with high turbulent level which are easier to predict.

All the experiments are made in one of the three full-scale test rooms situated at Aalborg University. The rooms have the following dimensions given as length, width and height, respectively.

5.4 m × 3.6 m × 2.4 m

5.4 m × 3.6 m × 2.6 m

8.0 m × 6.0 m × 4.5 m

The two small rooms correspond to a typical office room for two persons or a small meeting room. The large room has dimensions which are sufficient for experiments with industrial air distribution systems. All the rooms can be changed into smaller dimensions.

VENTILATION EFFECTIVENESS AND TEMPERATURE EFFECTIVENESS

The air quality and the efficient use of air are as important as thermal comfort. Different definitions of effectiveness for the evaluation of an air distribution system have therefore been commonly used during the last years.

The ventilation effectiveness shows how fast contaminant is removed from a room. It is defined as the ratio of concentration of the contaminant in the return opening to the concentration in areas of the ventilated room.

The ventilation effectiveness ε_{oc} in the occupied zone is given by

$$\varepsilon_{oc} = \frac{c_R}{c_{oc}} \tag{1}$$

where c_R and c_{oc} are concentration in return opening and mean concentration in the occupied zone, respectively.

A local ventilation index ε_p is defined as

$$\varepsilon_p = \frac{c_R}{c_p} \tag{2}$$

where c_p is the concentration in a point of the room, e.g. the breathing zone of a person. ε_p is also the reciprocal value of the normalized concentration in the point p.

A mean ventilation effectiveness $\bar{\varepsilon}$ is given by

$$\bar{\varepsilon} = \frac{c_R}{\bar{c}} \tag{3}$$

where $\bar{c}$ is the mean concentration in the whole room including areas outside the occupied zone.

Equations (1) to (3) assume that the supply flow is uncontaminated and it is also assumed that both the contaminant process and the flow are steady.

The efficient use of air in a room can also be studied by the temperature effectiveness ε_T of the occupied zone

$$\varepsilon_T = \frac{T_R - T_o}{T_{oc} - T_o} \tag{4}$$

where T_R, T_o and T_{oc} are temperature in return opening, temperature in supply opening and mean temperature in the occupied zone, respectively.

All the variables ε_{oc}, ε_p, $\bar{\varepsilon}$ and ε_T as well as the dimensionless concentration $c \,/\, c_R$ and the dimensionless temperature $(T-T_o)/(T_R-T_o)$ are independent of the Reynolds number in case of isothermal flow or flow with constant Archimedes' number and fully developed turbulence. The Reynolds number for a given geometry is proportional to the air change rate n, to the supply velocity u_o or to the flow rate q_o. The above-mentioned variables are therefore independent of n, u_o and q_o in case of fully developed turbulence. A self-similar temperature distribution in a room at differet Reynolds' number is for example shown by Nielsen (1974).

The Archimedes number Ar is given by

$$Ar = \frac{\beta \cdot g \cdot h \cdot \Delta T_o}{u_o^2} \tag{5}$$

where β, g and ΔT_o are volume expansion coefficient, gravitational acceleration and temperature difference between return flow and supply flow, respectively. u_o is the supply velocity and h is a characteristic height which e.g. can be the slot height of a celing diffuser or the height of a wall mounted low velocity air terminal device for displacement flow.

ROOM AIR MOVEMENT

One of the main purposes of a design procedure is to find the maximum velocity in the occupied zone. This velocity is in case of mixing ventilation also the maximum velocity in the reverse flow u_{rm} in situations where the main jets are outside the occupied zone. The velocity is often located close to the floor at a distance of 0.50 L to 0.7 L from the supply openings.

Most of the experiments made at Aalborg University include measurements of the maximum velocity in the occupied zone u_{rm} and measurements of the velocity distribution in the jets as well as measurements of the general velocity distribution. This paper will only review some of the u_{rm} measurements.

A normalized velocity as u_{rm} / u_o will also be independent of the Reynolds number or independent of n, u_o or q_o in case of a self-semilar flow. As argued ealier this type of air distribution takes place when fully developed turbulence and isothermal flow, or flow with constant Archimedes' number are present and it has for example been shown for jets and plumes by Turner (1979), and for room air motion by Müllejans (1963), Nielsen (1974), and Kato et al. (1988).

A constant value of the dimensionless ratio u_{rm} / u_o for different Reynolds' numbers means that

$$u_{rm} = const\ u_o \tag{6A}$$

$$u_{rm} = const\ q_o \tag{6B}$$

$$u_{rm} = const\ n \tag{6C}$$

All the experiments with displacement ventilation shown in this paper are made with wall mounted low velocity air terminal devices. The supply air flows directly into the occupied zone and the maximum air velocity u_x, in different distances from the opening x, is therefore the important design velocity of the system. Mathiesen (1989); and Sandberg and Mattsson (1991); have worked with stratified flow in the occupied zone in a room with displacement flow. Nielsen (1990 and 1992); has shown that the stratified flow in practice can be described by

$$\frac{u_x}{u_o} = K_{dr} \frac{h}{x} \tag{7}$$

for radial flow from a single air terminal device and by

$$\frac{u_x}{u_o} = K_{dp} \tag{8}$$

for plane flow from a number of air terminal devices located close to each other. K_{dr} and K_{dp} are functions of the Archimedes number and they are different for different types of air terminal devices. The structure of equations 7 and 8 shows that the normalized velocity u_x / u_o is independent of the Reynolds number. The velocity depends on the Archimedes number via K_{dr} and K_{dp}.

MIXING VENTILATION

Mixing ventilation - or jet ventilation - is an air distribution principle where the air movement in the room is governed by the momentum flow from the supply openings. Jets are entering the room outside the occupied zone and they entrain air from the room and generate a recirculating flow with low velocity in the occupied zone. The basic idea of mixing ventilation is to obtain an even velocity and temperature distribution in the occupied zone due to a high level of recirculation. Contaminant from a source in the room is likewise dissolved in the recirculating flow and removed by the air exchange.

Mixing Ventilation in Small Rooms

The room in figure 1 has a side wall mounted air terminal device (air terminal device D). The jet flows through the room in the ceiling region and it entrains air in quantities that correspond to an internal air change rate of 20 to 60 h^{-1}. An emission source is located in the middle of the room and the concentration of the tracer gas is measured along a vertical line through the source.

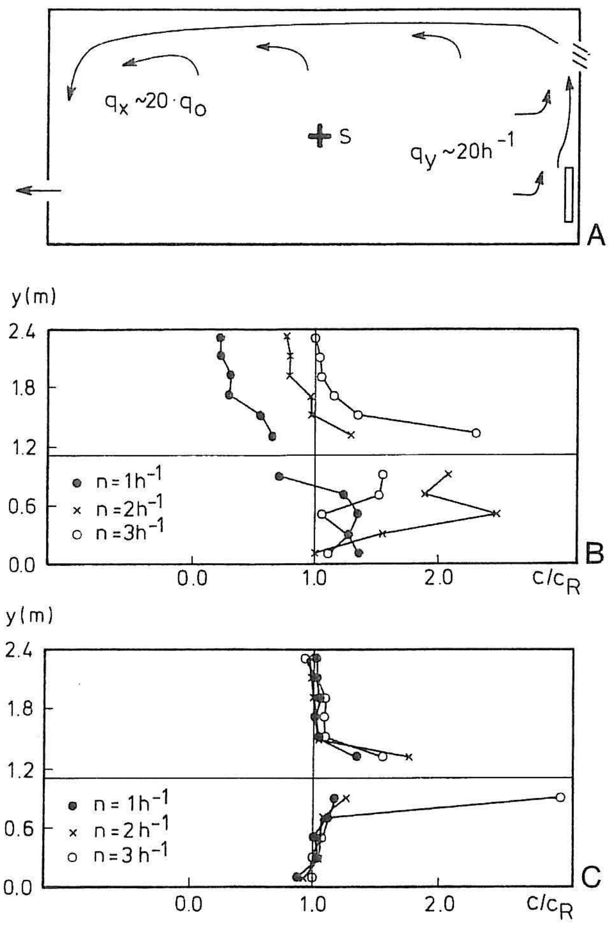

Figure 1. Concentration distribution in a room with mixing ventilation and an end wall mounted heater. The two lowest figures show a vertical concentration profile without and with supply of heating to the room. Air terminal device D. Measured by Heiselberg and Nielsen (1988).

Figure 1B shows vertical concentration profiles for three different air change rates in case of isothermal flow. The concentration profiles are normalized by the concentration in the return opening and the deviation between the three profiles indicates that the flow is not fully developed. It is further shown that the dimensionless concentration is getting close to 1.0 at the highest air change rate (3 h^{-1}) in more areas of the room.

Figure 1C shows a very significant change which is obtained when heating is supplied to the room. Entrainment in the plume will increase the recirculating flow in the room corresponding to an internal air change rate of 20 h^{-1} and it will further generate a horizontal movement in the stratified air in the middle of the room. A combination of those two effects produces a very even concentration profile independent of the air change rate to the room. The results do necessarily not indicate a high turbulent level everywhere in the room. It can be concluded that free convective flow in some situations is able to generate a very efficient mixing process in cases when a passive emission source is present in the room.

Generally figure 1 shows that the concentration has a high level around and directly below the source. The source is placed in an area of the occupied zone where the air velocity is very low and the tracer gas will reach a high concentration level before it is entrained and discharged with the surrounding air in the room. Measurements by Oppl (1969) show a similar effect when the source is placed in an area with a low velocity.

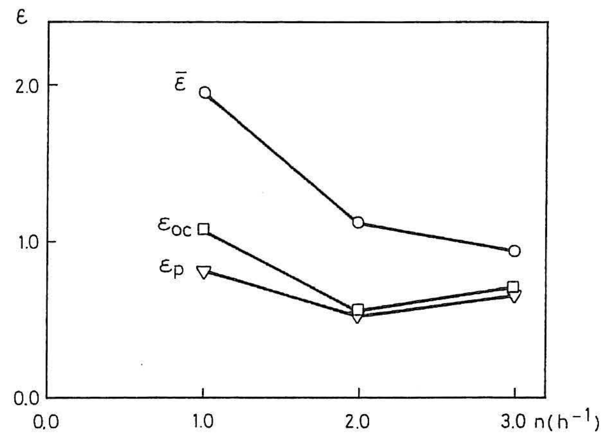

Figure 2. $\bar{\varepsilon}$, ε_{oc} and ε_p measured at isothermal flow in the room shown in figure 1.

Figure 2 shows the level of information which can be obtained from measurements of the ventilation effectiveness in different versions. The mean ventilation effectiveness $\bar{\varepsilon}$ indicates a very high level at the air change rate of 1 h^{-1}. The concentration profile shows that the concentration is high in the occupied zone but lower in the upper part of the room, see figure 1B. The low concentration in the ceiling region will therefore decrease the mean concentration $\bar{c}$ to a value which is low compared with the level in the occupied zone. The ventilation effectiveness ε_{oc} shows a more realistic level of effectiveness and the ventilation index ε_p shows the real situation at the given position of the measuring point. All three values are dependent on the air change rate n. The flow is not a fully developed turbulent flow although it is indicated from the development of the curves that constant values might be obtained at higher air flow rates. This is an important problem in connection with CFD simulations because turbulence models, as the k-ϵ model, will be unable to predict this effect.

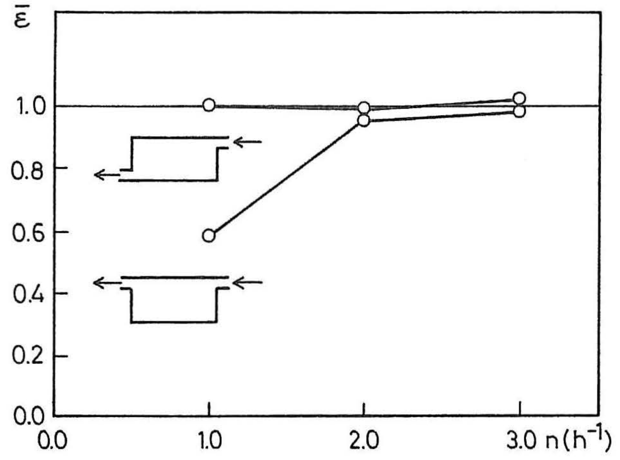

Figure 3. Mean ventilation effectiveness in a room with two different locations of the return opening. Air terminal device A. (Heiselberg and Nielsen 1987).

It is well known that the return opening only has a very small influence on the velocity distribution in a room, but it may have large influence on the ventilation effectiveness as discussed in the following example. Figure 3 shows the mean ventilation effectiveness in a room with a wall mounted supply nozzle (air terminal device A) and two different locations of the return opening. The flow is isothermal and it is obvious from the measurements that a high location of the return opening will decrease the effectiveness at low air change rates. The flow in the room is not fully developed and the lower part of the room will only obtain air movement if the return opening is located in this region.

The location of the return opening is also important for the effectiveness in case of non-isothermal flow. Low location is important in systems where heating takes place.

A fully developed turbulent flow will show proportionality between the velocity at a given location in the room and the air change rate n, see equation 6C. Figure 4 shows the maximum velocity in the occupied zone versus the air change rate. The measurements for the empty room are made at isothermal flow. The experiments have been made up to very high values of n (outside the comfort range) in order to study the proportionality, and it is seen that deviations take place at low air flow rate while equation 6C is fulfilled for higher air flow rates outside the comfort range.

Heating of the empty room with a heater will decrease the velocity u_{rm} as shown in figure 4. The curves are measured at a constant heat load (600 W) and a variable Archimedes number. It is therefore not possible to make any conclusion on the presence of fully developed flow.

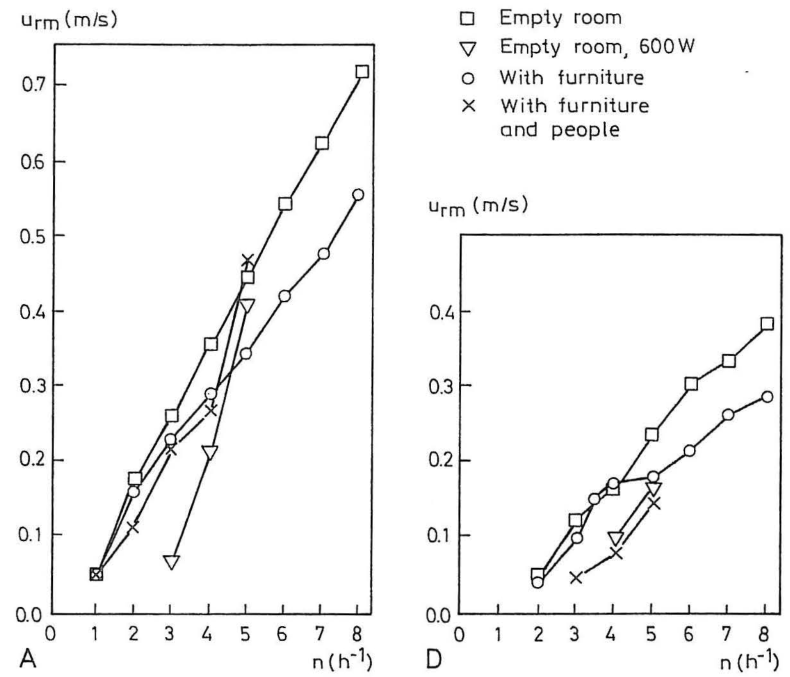

Figure 4. Maximum velocity in the occcupied zone of a room versus air change rate. Air terminal device A is a wall mounted nozzle and air terminal device D is a wall mounted diffuser with high entrainment.

The experiments in figure 4 do also show the situation with light furnishings and people in the test room. Four tables and four chairs will reduce the maximum velocity in the occupied zone and four persons seem to give further reduction, but other measurements may also show increased velocity level in rooms with obstacles (furniture). The measurements in the empty room are reported by Heiselberg and Nielsen (1988), and the furnished room by Gøthgen (1987).

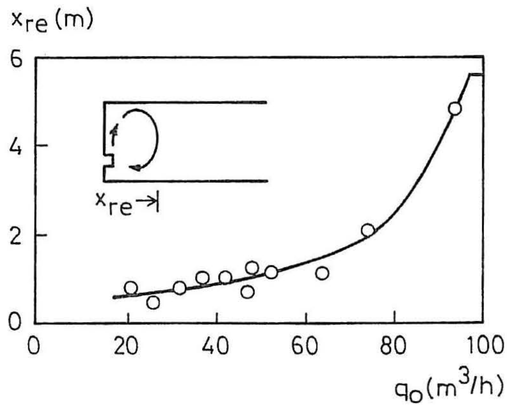

Figure 5. Penetration depth of a plane jet versus flow rate (Hau et al. 1985).

Figure 5 shows some experiments with isothermal two-dimensional flow and a small air change rate (0 to 2 h^{-1}). The recirculating flow in the occupied zone is very weak and it is not possible to measure any velocity of significance outside the supply jet. The figure shows the outcome of smoke tests and it is obvious that the air movement is very dependent on the flow rate which indicates low turbulent effects.

Mixing Ventilation in a Large Area

Experiments with mixing ventilation have been made in a full-scale room with the height 4.5 m in order to simulate the situation in industrial areas.

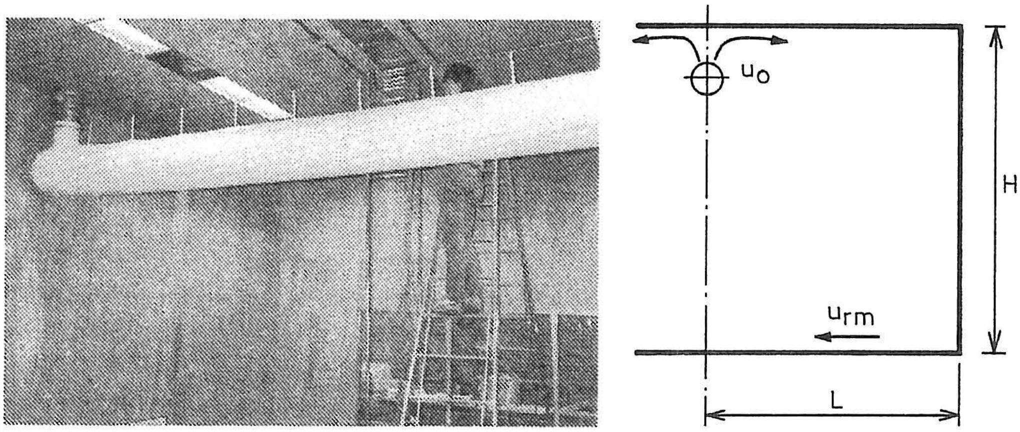

Figure 6. Fabric air flow duct with supply openings.

Figure 6 shows the supply device which consists of a fabric air flow duct with more rows of small circular openings. The duct is mounted below the ceiling and the air pressure keeps it inflated. Jets from the openings merged into two plane wall jets with opposite direction below the ceiling and two recirculating areas are obtained in the room. A large industrial area is ventilated by a number of air flow ducts mounted below the ceiling in a distance of 2 L from each other.

The maximum velocity u_{rm} in the occupied zone is in practice a linear function of the flow rate for $q_o \geq 500$ m^3/s, see figure 7. The velocity level is high but different layout of openings in the fabric duct will reduce the velocities to values down to 40% of the values shown in figure 7. Different dimensions of the ventilated area will of course also change the level of u_{rm}. The measurements are made at isothermal flow and they indicate a fully developed turbulent flow, see equation 6B. Ventilation with cool air will increase the velocity u_{rm} even without a reduction of the penetration depth of the wall jet below the ceiling.

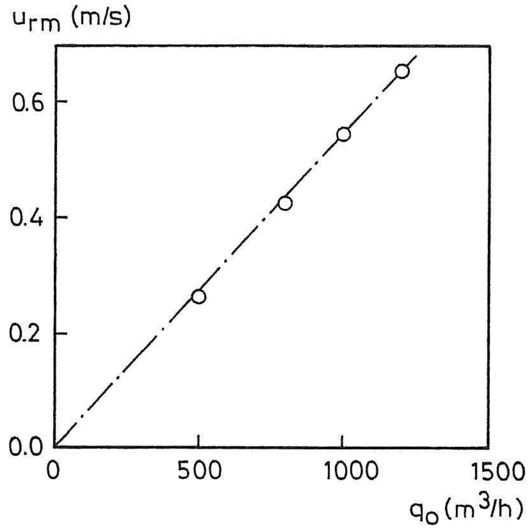

Figure 7. Maximum velocity in the occupied zone versus flow rate in an area with plane recirculating flow.

The flow in the room is mainly two-dimensional. This should also be expected because the boundary conditions will support this type of flow, but there are tendencies to higher velocities in two opposite corners of the four corners of the room. This type of problem is often met at measurements in rooms. The flow in the symmetric room discussed in the beginning of this chapter does also show some unsymmetric flow in areas with lower velocities as e.g. in the occupied zone.

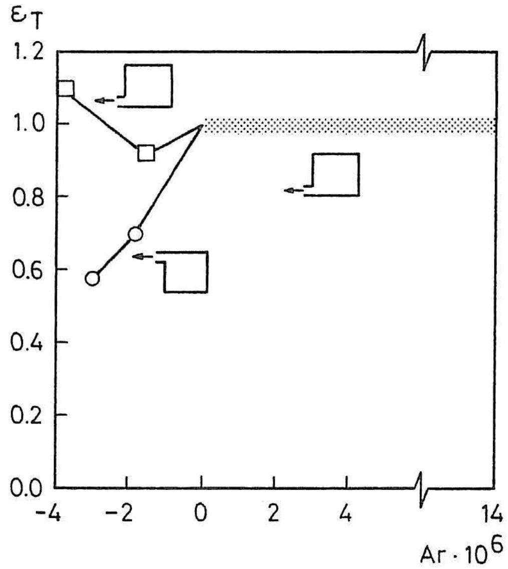

Figure 8. Temperature effectiveness ε_T versus Archimedes' number Ar.

Figure 8 shows the variation of the temperature effectiveness. The air distribution system seems to be very efficient in the mixing process in cases with supply of cool air. The temperature effectiveness is close to 1.0 for Archimedes' number up to $14 \cdot 10^{-6}$, and there is no variation in the temperatures in the occupied zone.

The location of the return openings is important in case of heating ($Ar < 0$). A high location of the return openings will remove air from the room with a temperature which is higher than the temperature in the occupied zone, and this is inefficient in case of heating, see figure 8. The necessary heat loss from the room is obtained as conduction through the walls, and this may explain the temperature effectiveness being slightly larger than 1.0 in situations where the return openings have a low location.

All the measurements shown in figures 7 and 8 are made by Bukh et al (1991).

DISPLACEMENT VENTILATION

Ventilation systems with vertical displacement flow have been used in industrial areas with high thermal loads for many years. Quite recently the vertical displacement flow systems have grown popular as comfort ventilation in rooms with lower thermal loads e.g. in offices.

Figure 9 shows the main principle of displacement ventilation. The airflow q_o is supplied directly into the occupied zone at low velocity from a wall mounted diffuser. The plumes from hot surfaces, from equipment and from persons entrain air from the surroundings in an upward movement, and cold downdraft may transport air down into the occupied zone. A stratification will take place in a height where the flow $q_{y1}-q_{y3}$ is equal to q_o in the situation shown in figure 9.

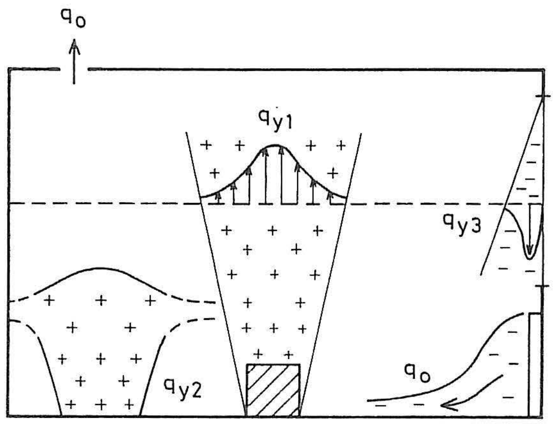

Figure 9. Room with displacement flow and natural convection.

The displacement flow system has two advantages compared with a traditional mixing system.

- An efficient use of energy. It is possible to remove exhaust air from the room where the temperature is several degrees above the temperature in the occupied zone, which allows a higher air inlet temperature at the same load.

- An appropriate distribution of contaminant air. The vertical temperature gradient (or stratification) implies that fresh air and contaminated air are separated, and the most contaminated air can be found above the occupied zone.

Temperature Distribution

One of the characteristic parameters in displacement ventilation is the vertical temperature gradient. Heat from heat sources is supplied to the room as convection and radiation. Free convection will raise the ceiling temperature compared to the surroundings, and radiation from the ceiling will then increase the temperature of the floor, which on the other hand is cooled by the cold supply flow from the diffuser. The total effect is a vertical temperature gradient which is rather similar at different locations due to the stratified flow in the room.

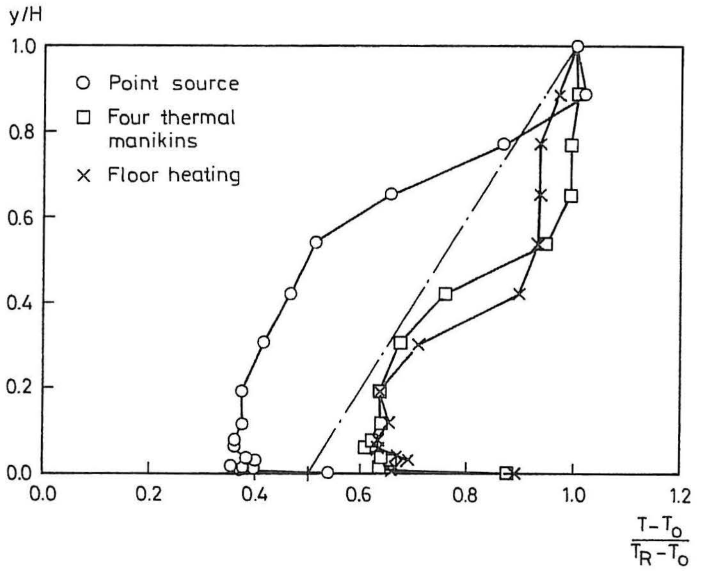

Figure 10. Vertical temperature gradients in a room with different heat sources at equal Archimedes' number (Christensen et al. 1990).

Figure 10 shows the vertical temperature gradient for different heat sources. The point source is a small cylindrical heater with open heating elements, 0.3 × 0.1$^{\varnothing}$. The thermal manikin is a black painted cylinder with the dimensions 1.0 × 0.4$^{\varnothing}$. The floor heating consists of more electrical heating carpets covering a large part of the floor surface.

The location of the normalized temperature gradient in figure 10 depends on geometrical extension and temperature of the heat source. A concentrated heat source as the point source will give a temperature distribution with a high temperature effectiveness $\varepsilon_T = 2.0$, while four thermal manikins generate a temperature distribution with a lower effectiveness $\varepsilon_T = 1.3$. Floor heating shows a bad utilization of displacement flow with a temperature effectiveness of $\varepsilon_T = 1.2$. It is likely that the ratio between radiation and convection is an important parameter. A high level of this ratio will displace the curves to the right side in figure 10 because it will increase the amount of heat supplied to the floor. Experiments with four thermal manikins covered with aluminium foil support this theory because the vertical temperature profile in this situation is displaced to the left side in figure 10.

The heat sources are located on the floor in the experiment shown in figure 10. A higher location of the sources will increase the temperature effectiveness.

Practical engineering methods within displacement ventilation assume a linear temperature distribution in the room from the value $0.5(T_R-T_o)$ at the floor to the value T_R at the ceiling. This distribution is shown in figure 10 by the dotted line.

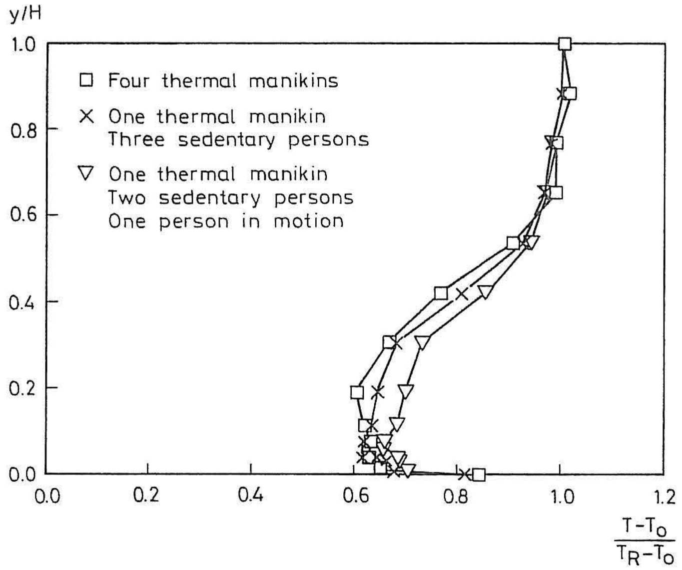

Figure 11. Vertical temperature gradients in a room with thermal manikins, sedentary persons and persons in motion (Christensen et al. 1990).

Figure 11 shows the vertical temperature distribution in a room with thermal manikins and persons. The manikins seem to give a sufficient thermal description of a person. It is especially important to see that a person in motion is unable to spoil the stratification, and the measurements show only a slight reduction in the temperature effectiveness. Other measurements with heavy activity and an open door to the test room do also confirm the large stability of the stratified flow in the room.

Concentration Distribution

Efficient use of energy is one of the advantages of displacement ventilation. Another advantage, mentioned in the introduction to this chapter, is an appropriate distribution of contaminated air with a separation between fresh and contaminated air.

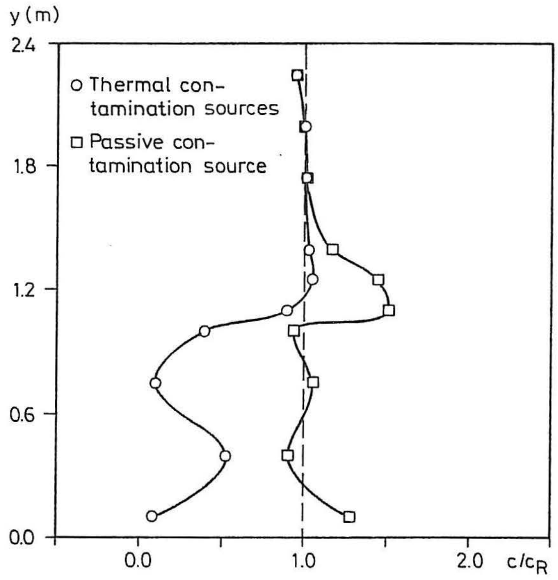

Figure 12. Vertical contaminant distribution in a room with displacement ventilation (Brohus et al. 1992).

The relative concentration distributions given in figure 12 show in one example a stratification with a high concentration in the upper area of the room and a low concentration in the lower part of the room. The heat load consists of four thermal manikins and the tracer gas (CO_2) is released in the plumes from the manikins. The average value of the concentration in the lower part of the room is 0.25 c_R corresponding to a ventilation index of $\varepsilon_p = 4.0$. The situation is different when the contaminant source is passive and located outside the plumes below the stratification height. The figure shows a high level of concentration in the room height corresponding to the height of the source. Very high concentrations may be obtained in this situation because the air movement is small in the area around the source and the contaminant is stabilized in a horizontal layer due to the temperature gradient.

The thermal boundary layer around a person entrains air from the surroundings. This air has a low content of contaminant in the lower part of the room and it may therefore protect the persons although the breathing zone is located above the stratification level. Measurements show that the average concentration of 0.25 c_R is found in the plume in heights where the concentration outside the plume is c_R. This effect has also been shown by Holmberg et al. (1990); and Stymne et al. (1991).

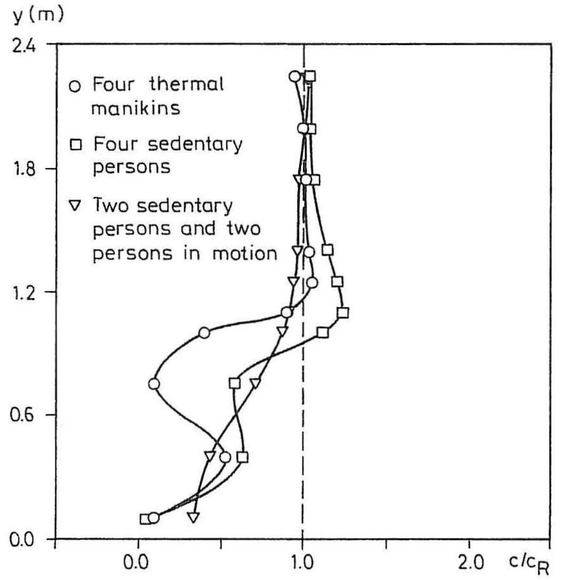

Figure 13. Concentration distribution in a room with thermal manikins, sedentary persons and persons in motion (Brohus et al. 1992).

It is important to preserve the stratification in the room when persons are present and in motion. Figure 13 shows the vertical concentration distribution with four thermal manikins. CO_2 is released in the plumes above the manikins. The relative concentration distribution for four persons is also shown and the CO_2 concentration is, in this case, the values obtained from the presence of persons in the room. It is shown that two persons in motion are able to smooth the vertical gradient slightly, but it is in all situations possible to observe a stratification of CO_2.

Velocity Distribution at the Floor

Wall mounted low velocity air terminal devices are often used in displacement ventilation. The air flow is supplied directly into the occupied zone and it is therefore important to have design methods which can predict the velocity distribution. A number of experiments in full-scale rooms have shown that the flow can be described as semi-stratified. The velocity u_x in the distance x from the diffuser is inversely proportional to x, see equation 7. The velocity level is individual for each diffuser (within certain limits), and it is a function of the Archimedes number (Nielsen 1990 and 1992). It is also shown by experiments that the dimensionless velocity distribution is fairly independent of the Reynolds number in the area of practical relevance (Nielsen 1988).

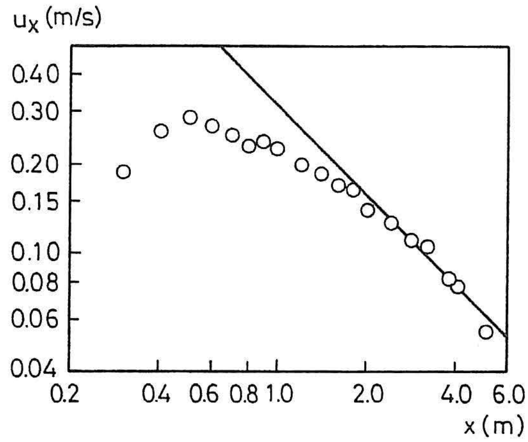

Figure 14. Velocity decay in the flow from a wall mounted air terminal device (Berg and Larsen 1991).

Figure 14 shows the velocity versus distance from the air terminal device. The velocity u_x is the maximum velocity in the profile and it is located 1 - 4 cm above the floor. The curve in figure 14 corresponds to equaiton 7. It is seen that the measurements are in agreement with equation 7 for $x > 2.0\ m$, and measurements on other diffusers show also good agreement very close to the diffuser. Equation 7 will in any case give a velocity equal to or higher than the actual velocity, and therefore a value which is suitable for a design procedures.

The velocity distribution from a low level diffuser depends on the Archimedes number. Figure 14 shows the initial acceleration of the air velocity resulting from buoyancy effect. A large temperature difference and a small velocity, corresponding to a large Archimedes number, will produce a large initial acceleration. Figure 15 shows this effect in the variation of K_{dr} for a given low level diffuser. (The characteristic temperature difference is in this case $T_{oc}-T_o$ when T_{oc} is the temperature in the height 1.1. m and T_o is the supply temperature). More of the diffusers show the linear relation between K_{dr} and $\sqrt{Ar}$ but it is not the case for all diffusers , especially not for the situation close to $\sqrt{Ar} \sim 0$.

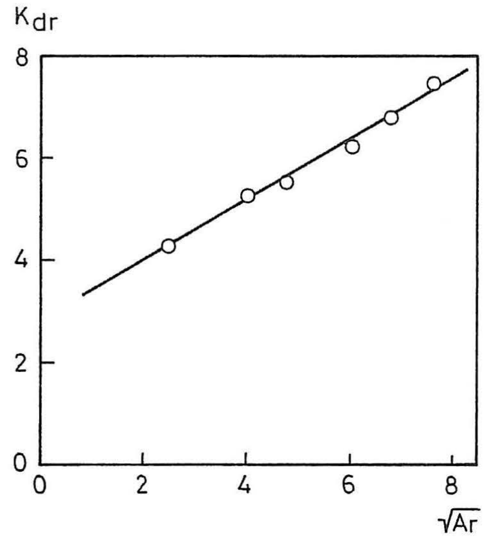

Figure 15. K_{dr} in equation 7 versus the Archimedes number.

CONCLUSION

Ventilation effectiveness is strongly dependent on the room air movement and the contaminant source location. Although the basic idea behind mixing ventilation is to obtain a complete mixing of the air, it can be shown that there exist gradients in contaminant distribution in the room and this will give rise to effectiveness different from 1.0.

The normalized concentration distribution is a function of the air change rate at a lower level of the flow, $n < 3\ h^{-1}$. Natural convection in a room seems to increase the mixing process in such a way that the normalized concentration distribution gets close to 1.0 at all air change rates.

It is shown that the location of the return openings is very important compared with the small influence this location has on the velocity distribution in the room.

The air flow rates in a room are often at a level where low turbulent effect takes place. This is shown for the maximum velocity in the occupied zone in the small test room with side wall mounted diffuser. The ventilation effectiveness is also strongly influenced by this effect and this stresses the importance of developments in turbulence models that can handle the problem when computational fluid dynamics is used for the prediction of the room air movement. Experiments at high air flow rates show self-semilar flow fields with constant values of the normalized maximum velocity in the occupied zone, and constant values of ventilation effectiveness and temperature effectiveness.

The ideas behind displacement ventilation is to achieve a high ventilation effectiveness and this is also obtained in many practical situation. It is shown that the temperature gradient and the temperature effectiveness are influenced by the type of heat source. A point source will give a high temperature effectiveness while sources with large areas located close to the floor will give smaller temperature effectiveness. Both stationary sources and persons in motion are used and the movement of persons has only a small influence on the effectiveness.

Ventilation effectiveness and vertical concentration gradients are also studied in a room with both stationary source and movable source. The vertical gradient is also present when persons are in motion. It is further shown that a passive, isothermal, contaminant source released in the occupied zone outside an area with convective flow may give use to a high concentration level.

The flow from a low level diffuser is supplied directly into the occupied zone in case of displacement flow. It is shown how the maximum velocity in this flow can be described as a function of flow rate and Archimedes' number for different diffuser designs. The description of the velocity distribution is suitable for a design procedure.

REFERENCES

Berg, S.-R. and H.H. Larsen. 1991. Private communication, Aalborg University.

Brohus, H., B.-O. Bøgh, F. Mogensen and T. Thomsen. 1992. Private communication, Aalborg University.

Bukh, B., L. Eskildsen and C. Jespersen. 1991. Private communication. Aalborg University.

Christensen, K.S., N.U. Christensen, B. Engsig, T. Gudmundsson, J. Jensen and H. Nielsen. 1990. Private communication, Aalborg University.

Gøthgen, H. 1987. Private communication. Aalborg University.

Hau, J. and T.K. Nielsen. 1985. Private communication. Aalborg University.

Heiselberg, P. and P.V. Nielsen. 1987. The Contaminant Distribution in a Ventilated Room with Different Air Terminal Devices. Proc. of the Int. Conf. ROOMVENT '87. Stockholm.

Heiselberg, P. and P.V. Nielsen. 1988. Flow Conditions in a Mechanically Ventilated Room with a Convective Heat Source. Proc. of the 9th AIVC Conf. ISBN 0 946075 40 9. Warwick: AIVC.

Holmberg, R.B., L. Eliasson, K. Folkesson and O. Strindehag. 1990. Inhalation-Zone Air Quality Provided by Displacement Ventilation. Proc. of the Int. Conf. ROOMVENT '90. Oslo.

Kato, S., S. Murakami, C.N. Kong and H. Nakagawa. 1988. Model Experiment on Indoor Climate and Space Air Distribution in Large-Scale Room. International Symposium on Scale Modeling. Tokyo: JSME.

Mathisen, H.M. 1989. Analysis and Evaluation of Displacement Ventilation. Ph.D.-thesis. Technical University of Norway.

Müllejans, H. 1963. Über die Ähnlichkeit der nicht-isothermen Strömung und den Wärmeübergang in Räumen mit Strahllüftung. Diss., T.H. Aachen.

Nielsen, P.V. 1974. Flow in Air Conditioned Rooms - Model Experiments and Numerical Solution of the Flow Equations. Ph.D.-thesis, Tech. University of Denmark.

Nielsen, P.V. 1988. Displacement Ventilation in a Room with Low-Level Diffusers. DKV-Tagungsbericht. ISBN 3-922-429-63-7. München: Deutscher Kälte - und Klimatechnischer Verein e.V.

Nielsen, P.V. 1990. Air Velocity at the Floor in a Room with Wall Mounted Air Terminal Device and Displacement Ventilation. (In Danish). Nordic Ventilation Groups. ISSN 0902-7513 R9004. Oslo.

Nielsen, P.V. 1992. Velocity Distribution in Rooms with Displacement Ventilation and Low Level Diffusers. Internal report. International Energy Agency. Energy Conservation in Buildings and Community Systems. Annex 20. (To be printed).

Oppl, L. 1969. Luftströmung in gelüfteten Räumen. Öl- und Gasfeuerung. Nr. 9.

Sandberg, M. and M. Mattsson. 1991. The Mechanism of Spread of Negatively Buoyant Air from Low Velocity Air Terminals. IV Seminar on "Application of Fluid Mechanics in Environment Protection 91". Gliwice.

Stymne, H., M. Sandberg and M. Mattsson. 1991. Dispersion Pattern of Contaminants in a Displacement Ventilated Room. Proc. of the 12th AIVC Conf. ISBN 0 946075 53 0. Warwick: AIVC.

Turner, J.S. 1979. Buoyancy effects in fluids. Cambridge: Cambridge University Press.

PAPERS ON INDOOR ENVIRONMENTAL TECHNOLOGY

PAPER NO. 17: H. Overby, M. Steen-Thøde: *Calculation of Vertical Temperature Gradients in Heated Rooms.* ISSN 0902-7513 R9046.

PAPER NO. 18: P. V. Nielsen, U. Madsen, D. Tveit: *Experiments on an Exhaust Hood for the Paint Industry.* ISSN 0902-7513 R9146.

PAPER NO. 19: L. Germann Pedersen, P. V. Nielsen: *Exhaust System Reinforced by Jet Flow.* ISSN 0902-7513 R9147.

PAPER NO. 20: P. V. Nielsen: *Models for the Prediction of Room Air Distribution.* ISSN 0902-7513 R9148.

PAPER NO. 21: M. Skovgaard, P. V. Nielsen: *Modelling Complex Inlet Geometries in CFD - Applied to Air Flow in Ventilated Rooms.* ISSN 0902-7513 R9149.

PAPER NO. 22: M. Skovgaard, P. V. Nielsen: *Numerical Investigation of Transitional Flow over a Backward Facing Step using a Low Reynolds Number $k-\varepsilon$ Model.* ISSN 0902-7513 R9150.

PAPER NO. 23: P. Kofoed, P. V. Nielsen: *Auftriebsströmungen verschiedener Wärmequellen - Einfluss der umgebenden Wände auf den geförderten Volumenstrom.* ISSN 0902-7513 R9151.

PAPER NO. 24: P. Heiselberg: *Concentration Distribution in a Ventilated Room under Isothermal Conditions.* ISSN 0902-7513 R9152.

PAPER NO. 25: P. V. Nielsen: *Air Distribution Systems - Room Air Movement and Ventilation Effectiveness.* ISSN 0902-7513 R9250.

PAPER NO. 26: P. V. Nielsen: *Description of Supply Openings in Numerical Models for Room Air Distribution* ISSN 0902-7513 R9251.

PAPER NO. 27: P. V. Nielsen: *Velocity Distribution in the Flow from a Wall-mounted Diffuser in Rooms with Displacement Ventilation.* ISSN 0902-7513 R9252.

PAPER NO. 28: T. V. Jacobsen & P. V. Nielsen: *Velocity and Temperature Distribution in Flow from an Inlet Device in Rooms with Displacement Ventilation.* ISSN 0902-7513 R9253.

PAPER NO. 29: P. Heiselberg: *Dispersion of Contaminants in Indoor Climate.* ISSN 0902-7513 R9254.

PAPER NO. 30: P. Heiselberg & N. C. Bergsøe: *Measurements of Contaminant Dispersion in Ventilated Rooms by a Passive Tracer Gas Technique.* ISSN 0902-7513 R9255.

PAPER NO. 31: K. S. Christensen: *Numerical Prediction of Airflow in a Room with Ceiling-Mounted Obstacles.* ISSN 0902-7513 R9256.

Department of Building Technology and Structural Engineering
The University of Aalborg, Sohngaardsholmsvej 57. DK 9000 Aalborg
Telephone: 45 98 15 85 22 Telefax: 45 98 14 82 43

PAPERS ON INDOOR ENVIRONMENTAL TECHNOLOGY

PAPER NO. 1: C. E. Hyldgård: *Aerodynamic Control of Exhaust.* ISSN 0902-7513 R8712.

PAPER NO. 2: Per Heiselberg, Peter V. Nielsen: *The Contaminant Distribution in a Ventilated Room with Different Air Terminal Devices.* ISSN 0902-7513 R8713.

PAPER NO. 3: Peter V. Nielsen, L. Evensen, Peter Grabau, J. H. Thulesen-Dahl: *Air Distribution in Rooms with Ceiling-Mounted Obstacles and Three-Dimensional Flow.* ISSN 0902-7513 R8714.

PAPER NO. 4: Peter V. Nielsen, Åke T. A. Mõller: *Measurements on Buoyant Wall Jet Flows in Air-Conditioned Rooms.* ISSN 0902-7513 R8715.

PAPER NO. 5: Peter V. Nielsen: *Numerical Prediction of Air Distribution in Rooms. Status and Potentials.* ISSN 0902-7513 R8823.

PAPER NO. 6: Peter V. Nielsen, Åke T. Mõller: *Measurements on Buoyant Jet Flows from a Ceiling-Mounted Slot Diffuser.* ISSN 0902-7513 R8832.

PAPER NO. 7: Peter Kofoed, Peter V. Nielsen: *Thermal Plumes in Ventilated Rooms - An Experimental Research Work.* ISSN 0902-7513 R8833.

PAPER NO. 8: Peter V. Nielsen, Lars Hoff, Lars Germann Pedersen: *Displacement Ventilation by Different Types of Diffusers.* ISSN 0902-7513 R8834.

PAPER NO. 9: Per Heiselberg, Peter V. Nielsen: *Flow Conditions in a Mechanically Ventilated Room with a Convective Heat Source.* ISSN 0902-7513 R8835.

PAPER NO. 10: Peter V. Nielsen: *Displacement Ventilation in a Room with Low-Level Diffusers.* ISSN 0902-7513 R8836.

PAPER NO. 11: Peter V. Nielsen: *Airflow Simulation Techniques - Progress and Trends.* ISSN 0902-7513 R8926.

PAPER NO. 12: M. Skovgaard, C. E. Hyldgaard & P. V. Nielsen: *High and Low Reynolds Number Measurements in a Room with an Impinging Isothermal Jet.* ISSN 0902-7513 R9003

PAPER NO. 13: M. Skovgaard, P. V. Nielsen: *Numerical Prediction of Air Distribution in Rooms with Ventilation of the Mixing Type using the Standard K, ε-Model.* ISSN 0902-7513 R9042.

PAPER NO. 14: P. Kofoed, P. V. Nielsen: *Thermal Plumes in Ventilated Rooms - Measurements in Stratified Surroundings and Analysis by Use of an Extrapolation Method.* ISSN 0902-7513 R9043.

PAPER NO. 15: P. Heiselberg, M. Sandberg: *Convection from a Slender Cylinder in a Ventilated Room.* ISSN 0902-7513 R9044.