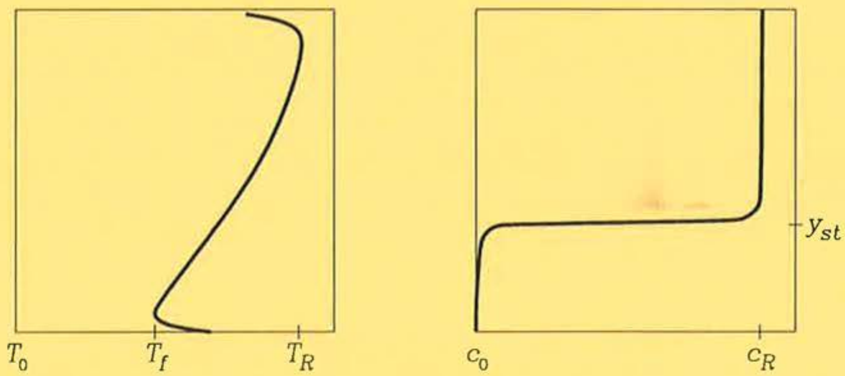
INSTITUTTET FOR BYGNINGS
DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL
AALBORG UNIVERSITET • AUC • AALBORG • DANMARK



INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 48

Presented at IEA Annex 26: Energy-Efficient Ventilation of Large Enclosures, Rome, 1995

PETER V. NIELSEN

VERTICAL TEMPERATURE DISTRIBUTION IN A ROOM WITH DISPLACEMENT VENTILATION

APRIL 1995

ISSN 0902-7513 R9509

Printed at Aalborg University

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

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 48

Presented at IEA Annex 26: Energy-Efficient Ventilation of Large Enclosures, Rome, 1995

PETER V. NIELSEN

VERTICAL TEMPERATURE DISTRIBUTION IN A ROOM WITH DISPLACEMENT VENTILATION

APRIL 1995 ISSN 0902-7513 R9509

VERTICAL TEMPERATURE DISTRIBUTION IN A ROOM WITH DISPLACEMENT VENTILATION

by

Peter V. Nielsen, Aalborg University

1. INTRODUCTION

A displacement ventilation system exploits the use of energy efficiently because it is possible to remove exhaust air from a room with a temperature that is several degrees above the temperature in the occupied zone. This process will allow a higher air inlet temperature at the same load in comparison with mixing ventilation.

It is necessary to have a design method for the temperature distribution used for instance in connection with the flow element method and the energy calculations.

The temperature distribution is also important in connection with thermal comfort in a room. It is necessary to consider the temperature gradient in the occupied zone, as well as the asymmetric radiation from the ceiling, in connection with the design of a displacement ventilation system and the evaluation of thermal comfort.

This paper will introduce five temperature distribution models with different levels of complexity.

2. VERTICAL TEMPERATURE GRADIENT

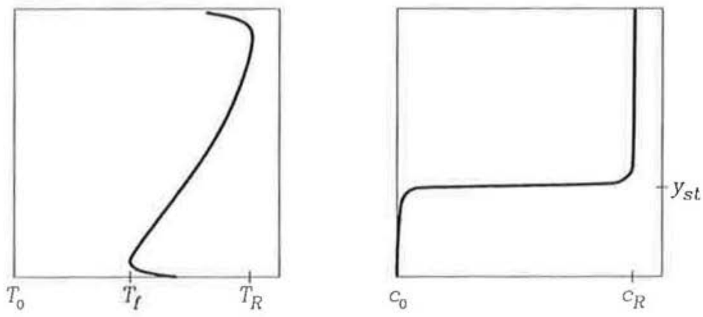


Figure 1. Vertical temperature distribution and vertical concentration distribution in a room with displacement ventilation.

The airflow to the room is supplied directly into the occupied zone by floor or wall-mounted diffusers. The plumes from hot surfaces, from equipment and from persons entrain air from the surroundings in an upward movement, and the airflow is extracted from the room by return openings in the ceiling. Figure 1 shows the vertical temperature distribution and the vertical concentration distribution in case some of the heat sources are contaminant sources. The right sketch in figure 1 shows that the concentration in a lower part of the room has the level c_o corresponding to the supply concentration. The plumes in the room will entrain fresh air (concentration c_o) up to a height where the total vertical volume flow is equal to the supply flow q_o. This height is called the stratification height y_{st}. The plumes continue above this height and the entrainment will generate a full mixing in the upper region with a concentration c_R corresponding to the concentration in the return flow as shown on the right-hand side of figure 1.

The temperature distribution is described by the energy transport equation, the radiation and the conduction through the surfaces. The energy transport equation and the transport equation for contaminant are identical in structure, and it is therefore possible to study the influence of radiation and conduction by comparing the two curves in figure 1. The temperature close to the floor T_f is high in comparison with the equivalent concentration distribution. The high level of temperature is due to radiation from the ceiling, and the gradients close to the floor and the ceiling indicate the corresponding heat transfer by convection. The vertical temperature distribution varies almost linearly with height compared with the concentration distribution. This may be the result of an influence from the vertical temperature distribution at the walls. Radiation is important for the energy flow in rooms with displacement ventilation and this is discussed in detail in the references [1] and [2].

The temperature gradient can with advantage be given in a dimensionless form. Figure 2 shows that the gradient has a limited variation compared with the variation which will be found for gradients in a dimensioned form.

The primary flow in a room with displacement ventilation expresses the similarity which is typical of fully turbulent flow. Vertical temperature gradient and stratification level of the contaminant can be described as a unique function of the Archimedes number independent of the velocity level in the room, see reference [4]. This Archimedes number can be given as

$$Ar_A = \frac{\beta g H \Delta T_o}{u_A^2} \tag{1}$$

where β, g and ΔT_o are volume expansion coefficient, gravitational acceleration and temperature difference between return and supply flow respectively. H is the room height and u_A is defined as

$$u_A = \frac{q_o}{A} \tag{2}$$

where q_o is the flow rate to the room and A is the floor area. The specific flow rate u_A is selected as characteristic velocity because the temperature distribution is governed by vertical displacement flow.

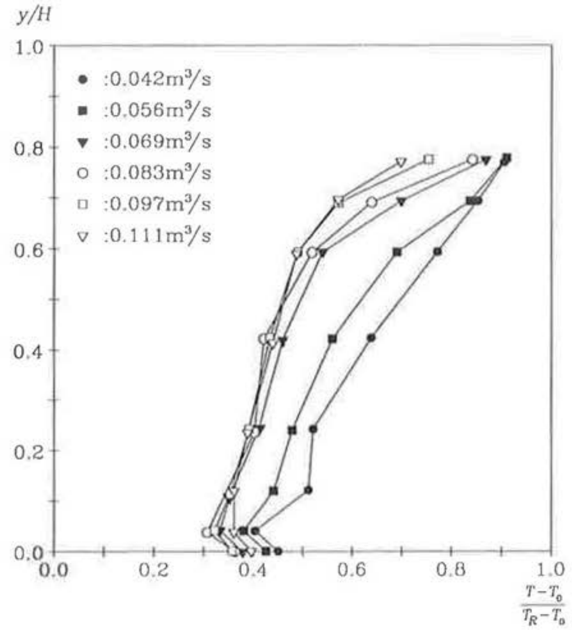


Figure 2. Vertical temperature distribution for different airflow rates, see reference [3].

The measurements shown in figure 2 are all made at constant heat load from a concentrated heat source. It is obvious that the dimensionless temperature profile is a weak function of the Archimedes number and that an increasing Archimedes number will decrease the normalized gradient slightly in the given situation.

It is a general experience that the vertical temperature gradients are identical at any location in the room outside areas with thermal plumes. This implies that the flow in that region formally can be expressed as a displacement flow, although the flow is a combination of a horizontal movement in the main body of the room and a vertical movement close to the walls, see references [4] and [5].

Figure 3 shows two vertical temperature gradients. They illustrate the identical temperature distribution in the main body of the flow as well as different temperature distributions close to the floor and the ceiling. Those two areas are governed by a cold gravity current from the diffuser and a warm gravity current from the vertical plumes respectively, see also references [1] and [6]. The temperature close to the floor T_f is defined as the average minimum temperature in the floor region. This temperature will often be linearly related to the temperature profile outside the stratified flow from the diffuser. The dimensionless temperature $(T_f - T_o)/\Delta T_o$ is for example 0.38 in the situation shown in figure 3.

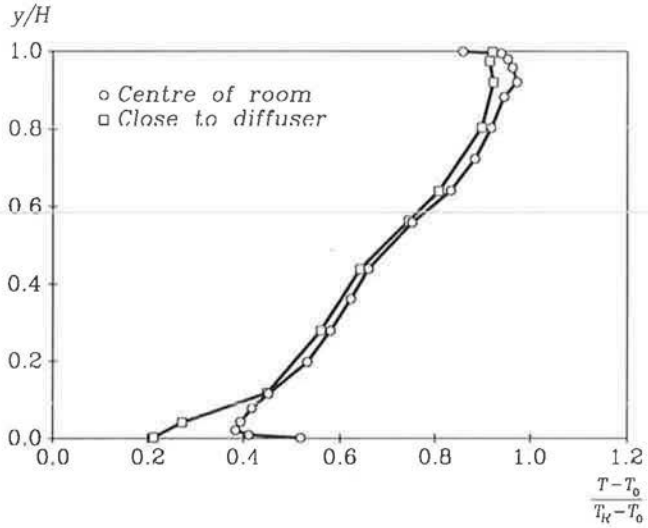


Figure 3. Two vertical temperature gradients in a room. One profile is located close to the diffuser and the other profile is located in the centre of the room. $Ar_A = 18 \cdot 10^4$.

3. TEMPERATURE GRADIENTS FOR DIFFERENT HEAT SOURCES

Measurements of vertical temperature gradients show that the type of heat source can be much more important than the flow conditions (Archimedes number). Figure 4 shows the vertical temperature gradient for different heat sources. The point heat source is a small cylindrical heater with open heating elements, 0.3 m × 0.1" m. The thermal manikin is a black painted cylinder with the dimensions 1.0 m × 0.4" m, and the floor heating consists of several electrical heating carpets covering a large part of the floor.

The location of the normalized temperature gradients in figure 4 depends on the geometrical extension and temperature of the heat source. A heat source as the point source will give a temperature distribution with relatively low temperatures in the occupied zone in comparison with the temperature in the return flow. This corresponds to a high system effectiveness. Four thermal manikins will generate a temperature distribution with a higher level in the occupied zone and consequently a lower system effectiveness. Floor heating shows a bad utilization of displacement flow.

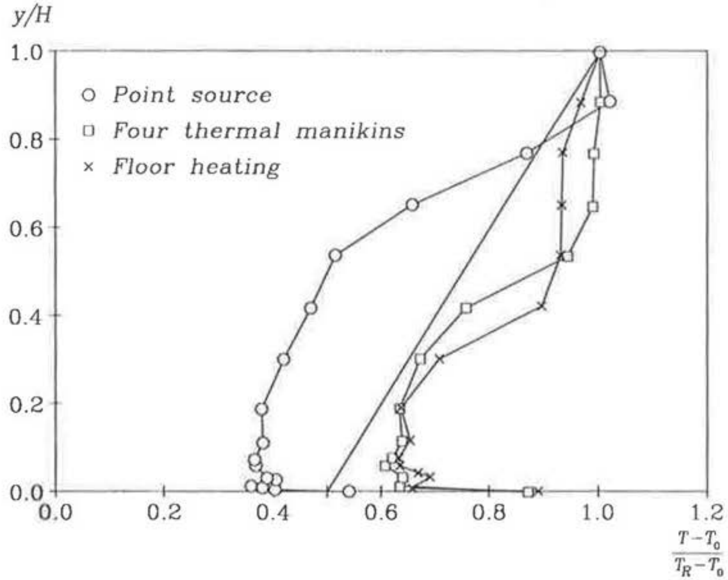


Figure 4. Vertical temperature gradients in a room with different heat sources. $Ar_A = 18 \cdot 10^3$.See reference [7].

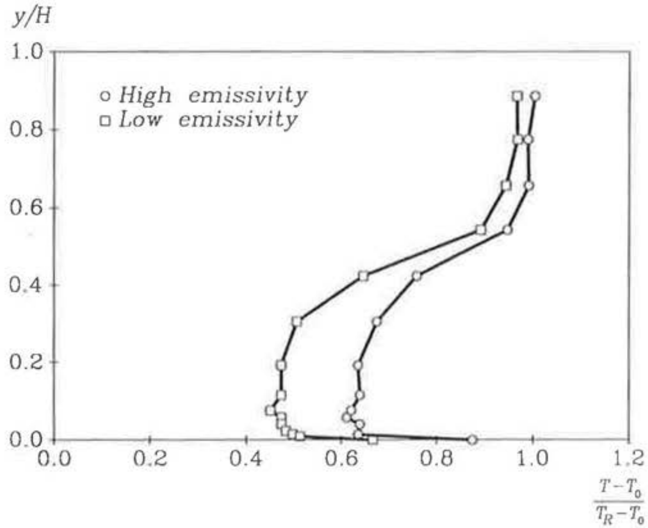


Figure 5. Vertical temperature gradients in a room with four thermal manikins which have a high and a low emissivity. $Ar_A = 18 \cdot 10^3$.

The ratio of radiation to convection is an important parameter. A high level of this ratio will displace the curves to the right because it will increase the amount of heat supplied to the floor. Experiments with four thermal manikins (1.0 m × 0.4" m) support this theory. Figure 5 shows how the vertical temperature profiles are displaced to the right-hand side of the figure when the emission is increased. The low emission is obtained by covering the cylinders with aluminium foil, and the high emission (0.95) is obtained in the standard situation where the cylinders are painted in a dull black colour.

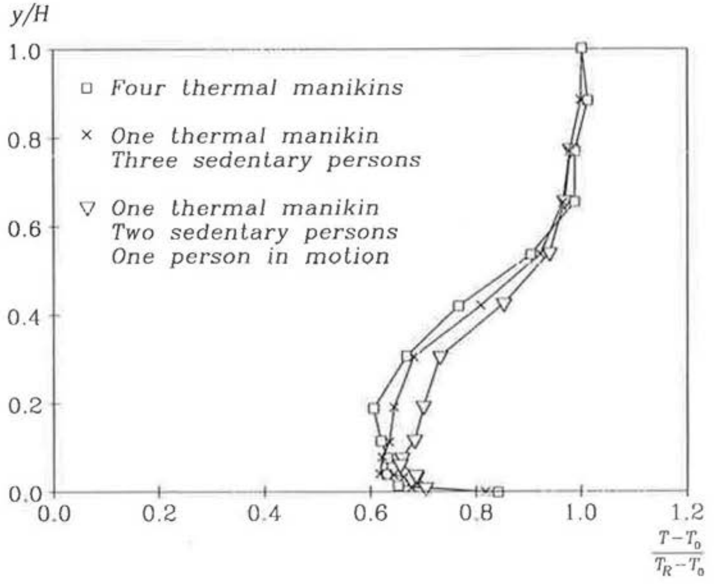


Figure 6. Vertical temperature gradients in a room with thermal manikins, sedentary persons and persons in motion, see reference [7].

Figure 6 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 notice that a person in motion is unable to spoil the stratification, and the measurements show only a slight reduction in the effectiveness of the system. Other measurements carried out during great activity and with an open door to the test room do also confirm the large stability of the stratified flow in the room.

4. MODELS FOR TEMPERATURE GRADIENTS

A design of a displacement ventilation system involves prediction of the vertical temperature gradient. This chapter shows five different practical methods with a varying level of complexities. The first method assumes a fixed value of T_f and a linear variation of the temperature distribution. The second method allows T_f to be a function of the specific flow rate to the room, while the third method takes account of both flow rate, heat load and type of heat sources. The last two methods deal with a non-linear temperature distribution.

4.1 Model with constant T_f

Measurements indicate that it is possible to make the simplified assumption that the temperature varies linearly with the height from the minimum temperature at floor level T_f to a maximum temperature at ceiling level. The ceiling level temperature is assumed to be equivalent to the return temperature T_R

$$T = \frac{y}{H}\left(T_R - T_f\right) + T_f \tag{3}$$

Skistad, see reference [8], suggests the following value for the normalized temperature at floor level

$$\frac{T_f - T_o}{T_R - T_o} = 0.5 \tag{4}$$

because the temperature often appears to be approximately half way between the supply air temperature and the extract air temperature. This applies to rooms of conventional height (2.5 m - 3.5 m) and normal heat loading. A comparison with figure 2 shows that the minimum temperature T_f has a limited variation when it is given in a dimensionless form which also may support the above-mentioned assumption. The dotted line in figure 4 shows the temperature distribution. It can be argued that the line represents a mean assumption for gradients from different types of heat sources.

4.2 Model with flow dependent T_f

The normalized minimum temperature T_f is slightly dependent on the airflow rate to the room. Mundt addresses this effect in reference [9] and gives the following figure 7 which shows the variation as a function of the specific airflow rate q_o/A. The figure summarizes a large number of measurements in different rooms. The temperature distribution in the room is assumed to be linear according to equation (3).

Li et al., see reference [1], have worked with different extensions of Mundt's model. They suggest a four point model which takes account of heat conduction at the ceiling and, furthermore, they suggest a multipoint model which takes account of various heat transfer modes including radiation between walls and conduction through the walls.

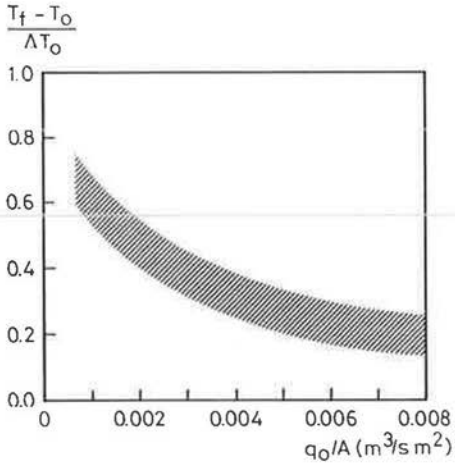


Figure 7. Minimum temperature at floor level T_f in a room with displacement ventilation versus specific flow rate.

4.3 Model with source and load dependent T_f

The temperature close to the floor T_f is strongly dependent on the heat sources in the room. Figure 4 shows that the dimensionless temperature varies from 0.35 to 0.65 for various heat sources and, therefore, it is important to have a design procedure which can take account of this effect.

Figure 8 shows a design chart which gives the normalized temperature at floor level for different types of heat sources. The point heat source is a small cylindrical heater with open heating elements. This heat source represents the lowest possible level for T_f. The ceiling light consists of four fluorescent tubes mounted 10 cm below the ceiling. It should be expected that they would give a low value of T_f, but radiation (light) seems to limit the system effectiveness although the tubes are mounted close to the ceiling. Sedentary persons are simulated by four black painted cylinders with the dimensions 1.0 m × 0.4" m, and the extensive heat source consists of three cylinders placed close to each other.

Experiments with people walking around in the room give the same variation in T_f as found for the extensive heat source.

It is assumed that the primary flow in a room with displacement ventilation is a fully developed turbulent flow. This means that a normalized temperature can be given as an unique function of the Archimedes number. Consequently, the Archimedes number Ar_A is used as a parameter in figure 8. The Archimedes number contains information on both thermal load in the room and flow rate to the room.

The temperature distribution in the room is assumed to be linear according to equation (3).

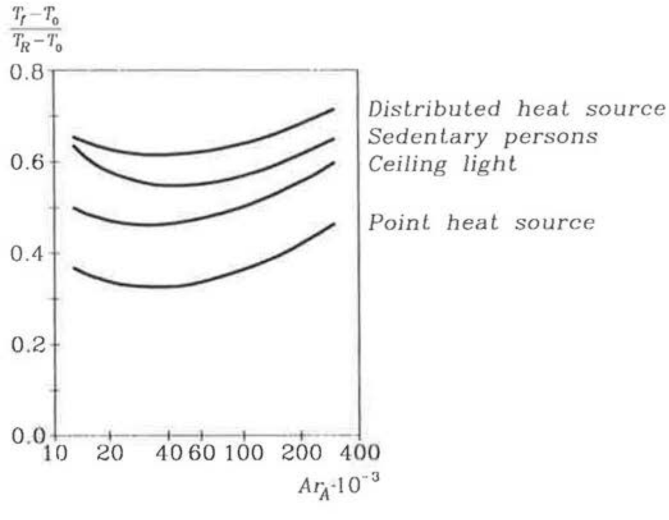


Figure 8. Minimum temperature at floor level T_f versus Archimedes number for different typical heat sources.

The results shown in figure 8 are found by experiments in rooms of conventional sizes (2.5 to 4.5 m high), and they must not be extrapolated to dimensions which are very different from these sizes. The results are also based on sidewall-mounted low velocity diffusers which will influence the results in comparison with special supply systems. It is, for example, possible to show that a system with perforated raised floor and ventilating carpet will obtain a non-dimensional minimum temperature of 0.2 for several heat sources, see reference [10].

The effect of a combination of different types of heat sources has not yet been studied. The method described in section 4.1 seems to be a practical procedure in this situation.

4.4 Model with non-linear temperature distribution

The vertical temperature distribution in a room with displacement ventilation will not always be linear as suggested by equation (3). Figure 4 shows e.g. a distribution from thermal manikins and floor heating which could be expressed as a combination of two straight lines.

A thermal plume in surroundings with a vertical temperature gradient may stratify because the increasing temperature will diminish the buoyancy force at a certain height. Figure 9 shows a plume which will obtain neutral buoyancy at the height y_t. The flow will continue up to the height y_m, due to the momentum flow, but it will return and stratify at y_t. The height to neutral buoyancy can be found from the following equation, see references [11] and [12]

$$y_t = 0.74\ \Phi_K^{1/4} \left(\frac{dT}{dy} \right)^{-3/8} \tag{5}$$

Φ_K is the convective heat flow from the source. It is assumed that y_t is measured from the virtual origin of the flow (floor level for a thermal manikin), and it is assumed that Φ_K is a small source which is unable to change the temperature gradient dT/dy.

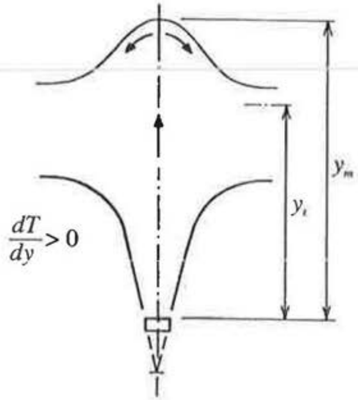


Figure 9. Vertical plume in a room with temperature gradient and stratification.

It is possible to obtain a special situation when the primary heat source will generate a plume with neutral buoyancy y_t within the height H. The source will influence the temperature distribution, shown in figure 9, because it is the only source in the room. The gradient will increase and y_t will decrease according to equation (5). It is assumed that T_f can be given from figure 8 and that the temperature above y_t is constant and equal to T_R because the stratified flow at y_t is the only source of heat that is available for the remaining displacement flow up to the return opening. The temperature gradient in the lower part of the room wil have the size

$$\frac{dT}{dy} = \frac{T_R - T_f}{y_t} \tag{6}$$

and the height to neutral buoyancy can be found from (5) and (6).

$$y_t = 0.62 \ \Phi_K^{2/5} \left(T_R - T_f\right)^{-3/5} \tag{7}$$

It is possible to obtain a flow with a neutral buoyancy height according to equation (7). Flow visualization in this situation shows that the air movement above y_t is a very slow and highly turbulent flow. It has different directions from time to time and the vortex diameter can be up to $H - y_t$. This air movement is very different from the flow which occurs when the upper zone is stratified and interrupted by plumes. The temperature distribution will in this case suppress a vertical flow in the main body of the room and measurements will only indicate a horizontal air movement outside the plumes and the wall areas, see references [4] and [5].

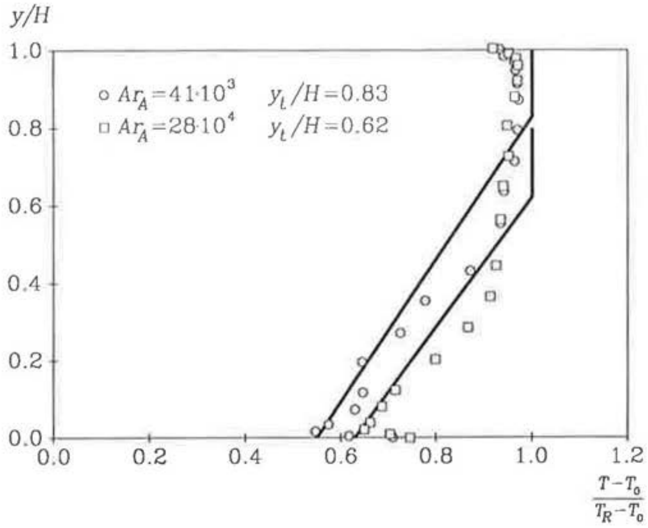


Figure 10. Vertical temperature distribution in a room with four thermal manikins.

Figure 10 shows the measurements of vertical temperature distribution in a room with four thermal manikins. The predicted temperature profiles are found from figure 8 and equation (7). They seem to give an improved description in comparison with a linear distribution over the entire height of the room.

The height to the upper zone y_{st} (stratification height) is smaller than y_t in all the measurements made in connection with figure 10. y_{st} must also be an important parameter, but the effect has not been studied.

It must be stressed that a non-linear temperature distribution will be created in many situation which are different from the situation described above. A high heat loss through the floor will e.g. create a temperature profile similar to the profiles shown in figure 10.

Vertical location of the heat source may also influence the temperature distribution. This effect is especially pronounced when the source is a point heat source with limited radiation. Figure 11 shows the measurements of two profiles for sources with different vertical locations y_{hs}. T_f is given from figure 8. It is obvious that profiles with a raised location of T_f do improve the results compared with a linear distribution in the entire height of the room.

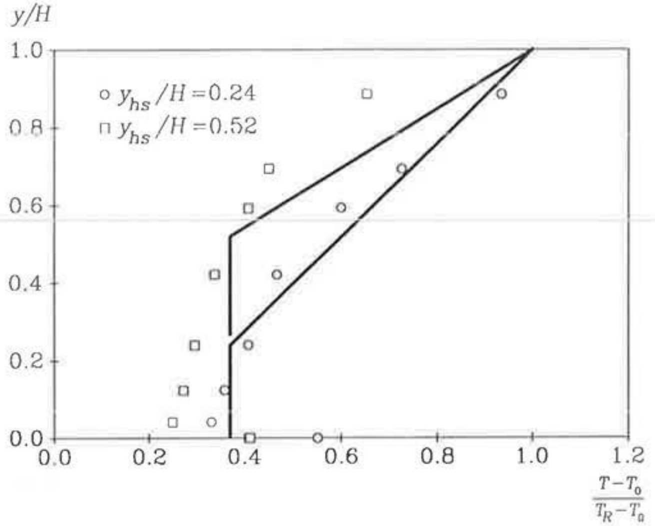


Figure 11. Temperature distribution in a room with a point heat source located at two different vertical positions y_{hs}.

5. CONCLUSIONS

It is necessary to have a model which can predict the vertical temperature distribution in a room. Measurements show that the temperature distribution often can be given as a linear function of the height of the room. It is also shown from measurements that the vertical temperature is strongly dependent on the type of heat source in the room and dependent on airflow rate and heat load.

Normally, a model is used which has a linear temperature distribution between a minimum temperature close to the floor and a maximum temperature close to the ceiling. The minimum temperature may either be a constanct fraction of a load dependent difference or it may be connected to the volume flow to the room.

Three new models are described. One model takes account of the different types of heat sources in the occupied zone as well as the characteristic Archimedes number of the flow. Another model is an extension which is valid for tall rooms and large enclosures where the flow from a heat source will reach the neutral buoyancy height within the room and give a non-linear temperature distribution. The last model takes account of the vertical location of the heat sources. All models express the temperature distribution as a constant gradient or a combination of a constant temperature area and a constanct gradient area. The models give an improvement of the design method for displacement ventilation.

Acknowledgement

Large parts of the experiments described in the paper are based on a number of research activities made at Aalborg University in connection with the education of M.Sc. students. The research activities have taken place from 1990 to 1995. All the experimental work has been supervised and linked up by the author who wants to give his acknowledgement to T. Gudmundsson, N.U. Christensen, H. Nielsen, B. Engsig, K.S. Christensen, J. Jensen, J. Stendahl, O. Christensen, L.K. Danielsen, L. Holst, L.B. Sørensen and E. Bjørn.

REFERENCES

[1] Li Y., Sandberg M., Fuchs L., Vertical Temperature Profiles in Rooms Ventilated by Displacement: Full-Scale Measurements and Nodal Modelling, Indoor Air, Vol. 2, 225 - 243, 1992.

[2] Li Y., Sandberg M., Fuchs L., Radiative Effects on Airflow with Displacement Ventilation: An Experimental Investigation, Energy and Buildings, Vol. 19, 263 - 274, 1993.

[3] Nielsen P.V., Hoff L., Pedersen L.G., Displacement Ventilation by Different Types of Diffusers, Proc. of the 9th AIVC Conference, ISBN 0946075 40 9, Warwick, 1988.

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

[5] Kofoed P., Kegel B., Turbulence Intensity and Buoyancy Effects in a Displacement Ventilated Room Measured with LDA, Proc. of the 6th International Conference on Indoor Air Quality and Climate INDOOR AIR'93, Helsinki, 1993.

[6] Mathisen H.M., Analysis and Evaluation of Displacement Ventilation, Doktor Ingeniøravhandling 1989:31, VVS-rapport 1989:2, Technical University of Norway, 1989.

[7] Nielsen P.V., Air Distribution Systems - Room Air Movement and Ventilation Effectiveness, Proc. of the ISRACVE Conference, ASHRAE, 1993.

[8] Skistad H., Displacement Ventilation, Research Studies Press Ltd., Somerset, 1994.

[9] Mundt E., Convection Flows above Common Heat Sources in Rooms with Displacement Ventilation, Proc. of the International Conference on Engineering Aero- and Thermodynamics of Ventilated Room, ROOMVENT'90, Oslo, 1990.

[10] Akimoto T., Nobe T., Takebayashi Y., Experimental Study on the Floor-Supply Displacement Ventilation System, accepted for ASHRAE San Diego Meeting, 1995.

[11] Morton B.R., Taylor G., Turner J.S., Turbulent Gravitational Convection from Maintained and Instantaneous Sources, Proc. Royal Soc., Vol. 234 A, p. 1, 1956.

[12] Mundt E., Convection Flows in Rooms with Temperature Gradients - Theory and Measurements, Proc. of the Third International Conference on Air Distribution in Rooms, ROOMVENT'92, ISBN 87-982652-6-1, Copenhagen, 1992.

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.

PAPERS 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.

PAPER NO. 32: S. G. Fox & P. V. Nielsen: *Model Experiments in 1990 and On-Site Validation in 1992 of the Air Movement in the Danish Pavilion in Seville.* ISSN 0902-7513 R9335.

PAPERS ON INDOOR ENVIRONMENTAL TECHNOLOGY

PAPER NO. 33: U. Madsen, N. O. Breum & P. V. Nielsen: *Local Exhaust Ventilation - a Numerical and Experimental Study of Capture Efficiency.* ISSN 0902-7513 R9336.

PAPER NO. 34: T. V. Jacobsen, P. V. Nielsen: *Numerical Modelling of Thermal Environment in a Displacement-Ventilated Room.* ISSN 0902-7513 R9337.

PAPER NO. 35: P. Heiselberg: *Draught Risk from Cold Vertical Surfaces.* ISSN 0902-7513 R9338.

PAPER NO. 36: P. V. Nielsen: *Model Experiments for the Determination of Airflow in Large Spaces.* ISSN 0902-7513 R9339.

PAPER NO. 37: K. Svidt: *Numerical Prediction of Buoyant Air Flow in Livestock Buildings.* ISSN 0902-7513 R9351.

PAPER NO. 38: K. Svidt: *Investigation of Inlet Boundary Conditions Numerical Prediction of Air Flow in Livestock Buildings.* ISSN 0902-7513 R9407.

PAPER NO. 39: C. E. Hyldgaard: *Humans as a Source of Heat and Air Pollution.* ISSN 0902-7513 R9414.

PAPER NO. 40: H. Brohus, P. V. Nielsen: *Contaminant Distribution around Persons in Rooms Ventilated by Displacement Ventilation.* ISSN 0902-7513 R9415.

PAPER NO. 41: P. V. Nielsen: *Air Distribution in Rooms - Research and Design Methods.* ISSN 0902-7513 R9416.

PAPER NO. 42: H. Overby: *Measurement and Calculation of Vertical Temperature Gradients in Rooms with Convective Flows.* ISSN 0902-7513 R9417.

PAPER NO. 43: H. Brohus, P. V. Nielsen: *Personal Exposure in a Ventilated Room with Concentration Gradients.* ISSN 0902-7513 R9424.

PAPER NO. 44: P. Heiselberg: *Interaction between Flow Elements in Large Enclosures.* ISSN 0902-7513 R9427.

PAPER NO. 45: P. V. Nielsen: *Prospects for Computational Fluid Dynamics in Room Air Contaminant Control.* ISSN 0902-7513 R9446.

PAPER NO. 46: P. Heiselberg, H. Overby, & E. Bjørn: *The Effect of Obstacles on the Boundary Layer Flow at a Vertical Surface.* ISSN 0902-7513 R9454.

PAPER NO. 47: U. Madsen, G. Aubertin, N. O. Breum, J. R. Fontaine & P. V. Nielsen: *Tracer Gas Technique versus a Control Box Method for Estimating Direct Capture Efficiency of Exhaust Systems.* ISSN 0902-7513 R9457.

PAPER NO. 48: Peter V. Nielsen: *Vertical Temperature Distribution in a Room with Displacement Ventilation.* ISSN 0902-7513 R9509.

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