Thermal Plumes in Ventilated Rooms

Vertical Volume Flux Influenced by Enclosing Walls

Kofoed, P.; Nielsen, Peter Vilhelm

Publication date:
1991

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

Presented at the 12th AIVC-Conference, Ottawa, Canada, 1991

P. KOFOED & P. V. NIELSEN
THERMAL PLUMES IN VENTILATED ROOMS - VERTICAL VOLUME FLUX INFLUENCED BY ENCLOSING WALLS
DECEMBER 1991 ISSN 0902-7513 R9155

AIR MOVEMENT & VENTILATION CONTROL WITHIN BUILDINGS

12th AIVC Conference, Ottawa, Canada
24-27 September, 1991

THERMAL PLUMES IN VENTILATED ROOMS
- Vertical Volume Flux Influenced by Enclosing Walls

Peter Kofoed
Sulzer Infra Group
Winterthur, Switzerland

Peter V. Nielsen
University of Aalborg
Aalborg, Denmark

Synopsis

The flow rate in thermal plumes are influenced by many factors. Influence by enclosing walls is one of them. This article presents simple symmetry considerations to calculate the flow rate in such flows, and they are experimentally verified as regards wall plumes. When the flow takes place near to enclosing walls the entrainment is influenced and a reduction of the flow rate is observed. For displacement ventilation this means a reduction of the stipulated necessary ventilating air flow rate when an air quality based design method is used.

Symbols

C_0	Contamination concentration in the occupied zone
C_R	Contamination concentration in the return air
Q'_0	Convective heat
T_F	Temperature of the floor
T_R	Temperature in the return air
V	Vertical volume flux
x	Vertical distance

1. Introduction

The main objective of ventilation is to provide good air quality for the occupants. For this purpose the necessary ventilating air change rate must be determined. Within displacement ventilation the estimation is closely related to the air flow rate in the thermal plumes when an air quality based design method is used. The vertical volume flux in a plume is influenced by many factors. Placement of the flow in relation to surrounding walls is one of them. This reduces the entrainment and is the subject of this article.

1.1 Displacement Ventilation

The qualitative behavior of displacement ventilation may be regarded as well-known due to many publications in the recent years, ref. **/1, 5, 10, 14, 15/**.

Good air quality is achieved by a separation principle where fresh air and polluted air are separated. The upward moving thermal plumes generate an upper zone with mixing flow where the contamination concentration is higher than in a lower clean zone. The characteristic layer between the two zones, the so called front, may be visualised by smoke experiments, ref. **/6 pp. 14-15, 8 pp. 75 - 78/**. The vertical contamination distribution also confirms the separation principle since a sudden step in concentration can be seen, see e.g. Heiselberg & Sandberg **/3/** or Holmberg et Al. **/4/**.

The principle of displacement ventilation appears in figure 1. The front separates the room in two zones and the level of the front depends on the relationship between the ventilating air flow rate and the flow rate in the thermal plumes. The stratification boundary will stabilize at a level where these two flow rates are equal, below there will be a clean zone. This is a result of the general upward moving air outside the plumes since they have not yet entrained all the fresh supply air. When plumes rise they continuously entrain air from the surroundings. As a consequence an increase of the ventilating air flow rate will rise the level of the front. On the other hand a too little amount will give a too low level.

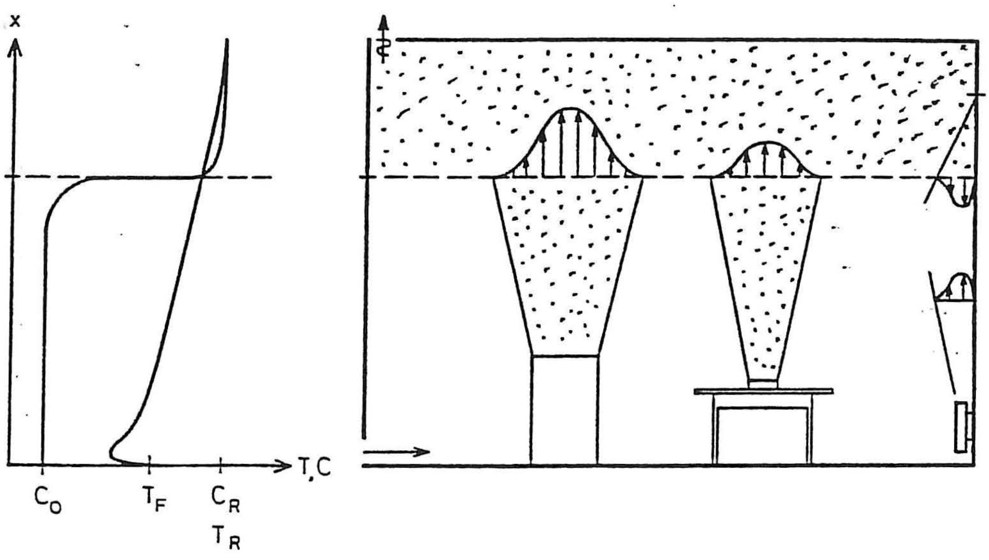

Figure 1. Displacement ventilation flow with two zones. The graphs to the left show the temperature and the contamination distributions.

1.1.1 Air Quality Based Design

One could think immediately that the ventilating air flow rate should be determined so that the clean zone includes the entire occupied zone, i.e. about up to 1.8 m height above floor level. However, such an approach leads to too high air change rates, considerably higher than usual.

Holmberg et Al. /4/ have carried out inhalation zone air quality measurements with low normal air change rates. Their investigations still favour displacement ventilation even when the front is at a level below the inhalation zone. The clean air below is entrained and transported by the convection boundary layer around the human body from the floor level up to the inhalation zone. In this way the air quality in the inhalation zone should be better than the quality of the surrounding room air at the same level. A choice of 1 to 1.2 m as a front level height seems to give reasonable ventilating air flow rates and also to assure a good air quality in the inhalation zone.

1.2 Scope

This article presents the influence on entrainment when convective flows take place near to enclosing walls or to other thermal plumes. Simple symmetry considerations are introduced and they are experimentally verified in the case of a wall plume.

2. Theory on Plumes

Turbulent buoyant plumes have been investigated for more than 50 years. Schmidt /13/ and Rouse et Al. /12/ are early workers. Later Popiolek /11/ gives an analysis. For the vertical volume flux in a free plume the following power law is found

$$V \approx Q_0^{1/3} \; x^{5/3} \qquad (1)$$

2.1 Symmetry Considerations

When the thermal flow rises near to enclosing walls the entrainment is affected, ref. **/7, 8/**. This may also be the case if two or more convection flows influence each other. Coanda effects may be present in flows near to walls so that they are no more axisymmetrical. However, the following symmetry considerations may give some idea of the vertical volume flux in such flows.

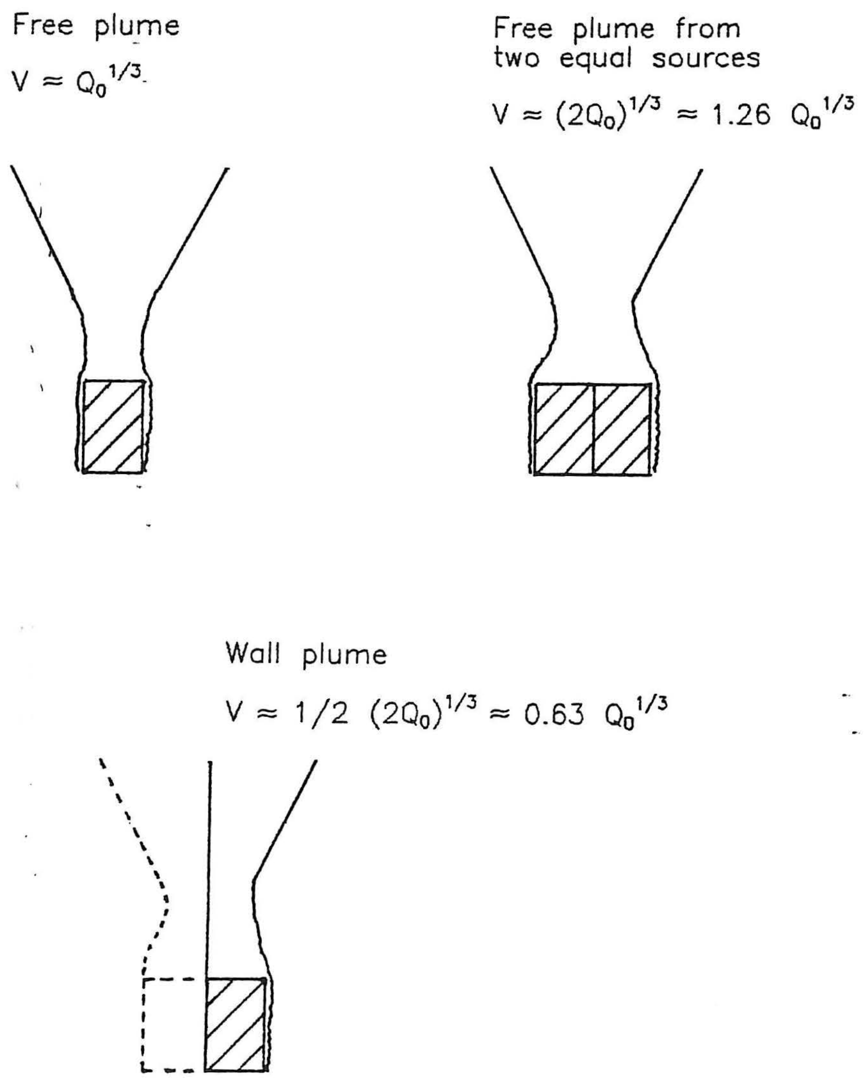

Figure 2. Symmetry considerations regarding vertical volume flux in thermal plumes are illustrated: free plume, two flows forming one plume, wall plume.

Free plume:

$$V \approx Q_0^{1/3} \tag{2}$$

Two equal sources close together forming one plume:

$$V \approx (2\ Q_0)^{1/3} \tag{3}$$

$$V \approx 1.26\ Q_0^{1/3} \tag{4}$$

Wall plume:

$$2V \approx (2\ Q_0)^{1/3} \tag{5}$$

$$V \approx 0.63\ Q_0^{1/3} \tag{6}$$

Plume in a corner:

$$4V \approx (4\ Q_0)^{1/3} \tag{7}$$

$$V \approx 0.40\ Q_0^{1/3} \tag{8}$$

The influence by the source geometry is neglected and only the heat power is taken into account. The above mentioned symmetry analysis leads to the result that the flow in a buoyant wall plume amounts to 63 % of the flow rate in the corresponding free plume, for a plume in a corner it is 40 %. Further two equal sources close to another form a flow where the vertical volume flux amounts to 126% of that from a single free source.

If the symmetry argumentation holds true, for displacement ventilation with air quality based design this means that the ventilating air flow rate may be reduced when the thermal flows take place near to walls or close to another.

3. Experimental Technique

The experimental investigations are carried out in a full-scale clima chamber at the Institute of Building Technology, University of Aalborg, Denmark. The dimensions of the room are 8x6x4.6 m. Futher a displacement ventilation system with two wall-mounted diffusers and two exhaust openings in the ceiling are installed so that the room can be ventilated and different vertical temperature gradients created, if required.

Two different circular heat sources are used to generate the convection flow. A vertical black painted closed cylinder is chosen to simulate the flow from a person. The cylinder is 1000 mm high and has a 400 mm diameter. Inside the source four electric bulbs are placed. When a power of 100 W is induced, the source has a surface temperature similar to the one of a person. During the measurements the source has been situated directly on the floor. The other source consists of a steel tube, height 150 mm and diameter 50 mm, with hot wire inside. The power is 125 W. During the measurements the source is vertically placed in mineral wool and the air is sucked through the source from below. The distance from the top of the source to the floor is 0,25 m.

3.1 Zero Method

A so called zero method has been used for the vertical volume flux measurements. First smoke visualizations by introducing smoke into the source zone have taken place to assure the vertical direction of the plume flow. Next the air is exhausted above the heat source with a circular exhaust hood. The exhausted air volume can be controlled by a helping ventilator and the air flow rate is measured with an orifice. Figure 3 shows a scheme of the set up.

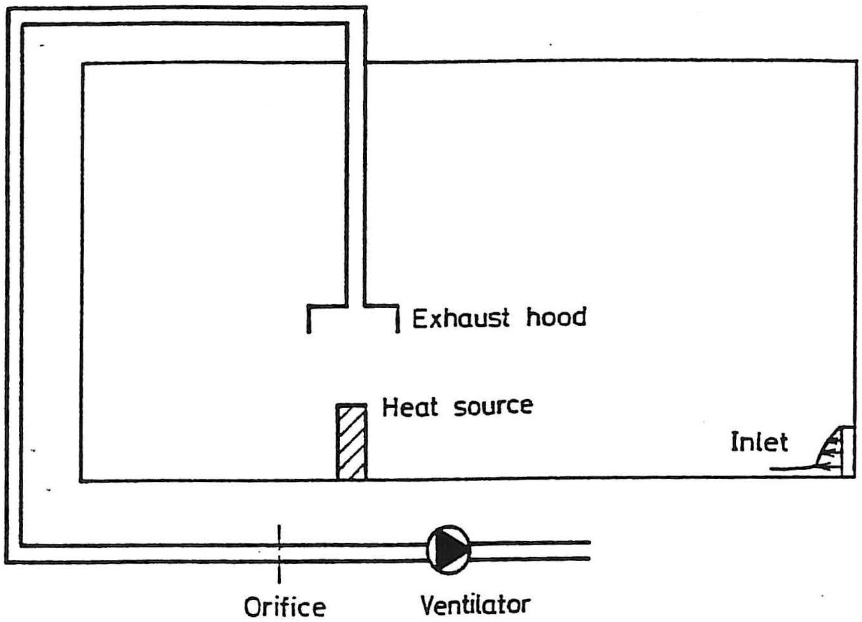

Figure 3. Scheme with the zero method set up: heat source, exhaust hood, orifice, helping ventilator, etc. The vertical temperature gradient is measured outside the flow. At the border of the hood or at the heat source smoke can be introduced.

At border of the exhaust hood from time to time small amounts of smoke are introduced, in this way it is controlled if no horizontal flow takes place. When this is the case one may assume that the same amount of air is exhausted through the hood as the vertical volume flux in the buoyant jet from the heat source at the same height.

Hoods with different widths and side heights have been investigated to improve the method. One limit is reached when the effective width of the flow (including the axis wandering) is wider than the diameter of the hood. On the other hand, the hood may not be to wide since, in this case, the horizontal velocities that determine the equilibrium between the exhaust and the air coming into the hood are very low. Practical carrying out of experiments and comparing with results of an extrapolation method, ref. **/7, 8/**, form the basis for the choice of hood diameter. A diameter of 1.60 m is convenient for measurements in 2.00 m height above the floor when the heat sources are of the type described in **/chapter 3/**. The necessary side height is dependent on the vertical velocity of the flow, high velocities giving high values. The maximum mean velocities in 2.00 m height above the floor from a heat source such as a sitting person are of the order 0.2 m/s, see Mierwinski **/9/**. A side height of 0.20 m is found suitable, in this case the flow inside the hood remains stable. If considerable higher mean velocities were present the side height should have been higher to prevent fall outs due to pressure accumulation in the hood.

3.1.1 Accuracy of the Zero Method

Since the zero method depends on individual observations by an operating person the question about accuracy soon arises. Therefore, the results of the zero method have been compared with reference results of an extrapolation method, ref. **/8 pp 123-135/**. Further, the same experiment has been carried out several times to find the spread of the results. On this basis it is concluded that the zero method gives the same result for the volume flux as the extrapolation method when investigating axisymmetrical buoyant plumes. The volume flux can be estimated with an error about of 10 % of the measured value. The zero method is easy to use and quickly it gives results. The investigated flow does not have to be axisymmetrical or fully developped. Further, flows influenced by enclosing walls, i.e. wall jets, comprise no problems since, in this case, the smoke observations become more stable.

4. Measurements Results

The heat source has been placed free, forming a free plume, or close to a wall, forming a wall plume. The measuring of vertical volume flux in the generated plume has taken place 2.00 m above the floor. Further the measurements are carried out with two different vertical temperature gradients in the surroundings and calculated between 0.10 m and 2.00 m above the floor the values are 0.3 K/m or 0.6 K/m. The measured volume fluxes appear as a table in figure 4 and grafically in figure 5.

Heat source & heat supplied	Vertical tempgrad (K/m)	Vertical volume flux: Free plume (m^3/h)	Vertical volume flux: Wall plume (m^3/h) (% of f.pl)
Tube dia. 50 mm 125 W	≅ 0.3	238	150 (63 %)
	≅ 0.6	200	125 (63 %)
Cylinder dia. 400 mm 100 W	≅ 0.3	200	125 (63 %)
	≅ 0.6	175	112 (64 %)

Figure 4. Vertical volume flux in free plumes and corresponding wall plumes 2.00 m above the floor at two different vertical temperature gradients

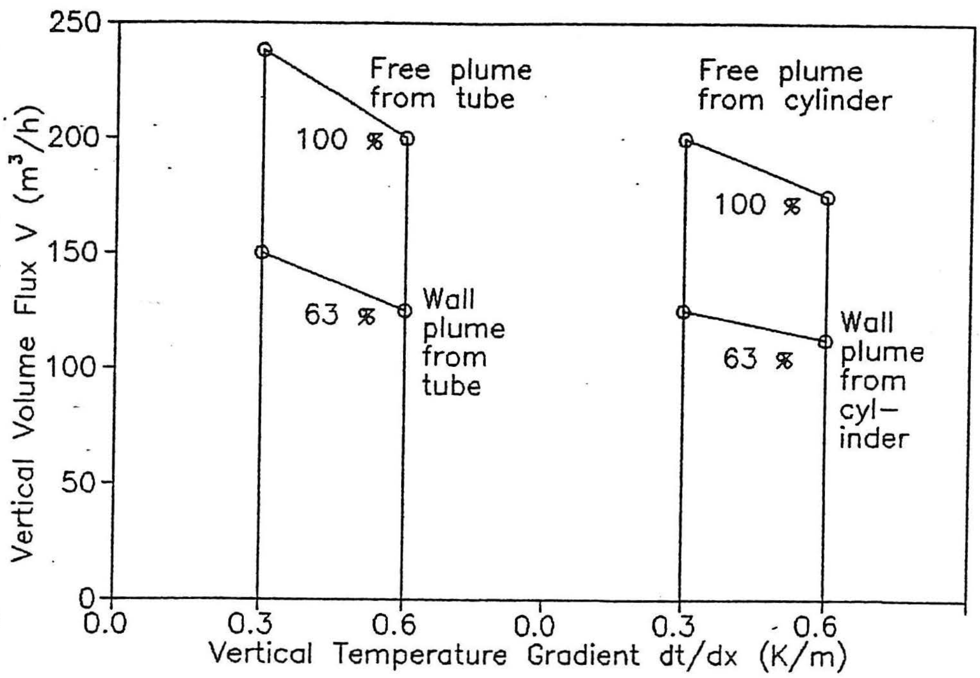

Figure 5. Vertical volume flux in free plumes and corresponding wall plumes 2.00 m above the floor. In both cases (tube left and cylinder right) an increase of stratification from 0.3 to 0.6 K/m leads to a reduction of the flow rate. Also placement plays a role, in wall plumes the flow rate is 63 % of that in the corresponding free plume.

4.1 Influence by Placement

The wall influences the entrainment in the plume, see figure 4 and 5. It looks like, that the volume flux in a wall jet amounts to around 63 % of the volume flux in the corresponding free jet. However, for each single wall plume & free plume comparison it is important that the two vertical temperature distributions are similar, that the two vertical temperature gradients have the same value and thirdly, that the temperature levels in the room are the same in the two cases. These demands are fulfilled and leaving further discussion out of account it may be concluded that:

The zero method measurement results verify symmety consideration of **/chapter 2.1/** as regards wall plumes, see equations 2 and 6. I.e. the vertical volume flux in a wall jet amounts to around 63 % of the volume flux in the corresponding free jet at the same vertical temperature gradient.

4.2 Influence by Stratification

The influence by vertical temperature gradients on the flow is discussed by several authors, ref. **/2, 7, 8, 10/**. It leads to a reduction of the flow rates.

Two different vertical temperature gradients have been present during the investigations, approximately 0.3 and 0.6 K/m. According to figure 4 and 5 an increase of the gradient involves a decrease of the volume flux as expected. Immediately it seems that the influence by the vertical temperature gradient depends on the type of heat source. Immediately it may be concluded that the relative reduction of the flow rate in a free jet and the corresponding wall jet has the same value: For the tube and cylinder a 17 and 11 % reduction, respectively, when the gradient increases from 0.3 to 0.6 K/m.

When making such conclusions it is important to take the mutual vertical temperature gradients and surface temperatures into consideration. Perhaps the vertical temperature gradient is not the only factor influencing the plume flow. Local cooling by forced convection or radiant heat exchange from the source to the surrounding surface may have a great influence too.

5. Conclusion

Several advantages of the zero method is reported: the method is very easy to use and the results are quickly produced. There is no claim on the velocity distributions, e.g. such as axisymmetrical Gaussian shaped profiles. As a result unstable flows from extensive heat sources and flows influenced by enclosing walls may be investigated, i.e. the buoyant flows that actually take place in ventilated rooms.

The method has some disadvantages too: it only gives information about the vertical volume flux in the plume and therefore it is not suitable for fluid dynamic investigations. Further the measurement results depend on the operating person who individually determines the exhausted air flow rate that estimates the vertical volume flux in the plume. However, with some experience reliable results may be produced, and the resolution is evaluated better than ± 10 %.

The experiments on wall plumes and corresponding free plumes verify a 63 % rule, i.e. the vertical volume flux in a wall plume amounts to around 63 % of the volume flux in the corresponding free plume at the same vertical temperature gradient. Thereby the symmetry considerations are verified as regards wall plumes.

The investigations further implie the statement that increasing stratification reduces the vertical volume flux in plumes. This observation is consistent with that from other authors.

Further an investigation of buoyant plumes in a corner and of the flow when two equal sources are placed close to another are suggested, and if possible to verify the symmetry considerations.

It seems reasonable to use simple symmetry argumentation to estimate the vertical volume flux when sources are placed near to walls or close to another, forming only one flow. This will reduce the stipulated necessary ventilating air flow rate when an air quality based design method for displacement ventilation is used.

References

1- Brügger, P. & B. Kegel : Displacement Ventilation for an Office Building with Triple Glaced Windows, Clima 2000, Sarajevo, Sept. 1989.

2- Fitzner, K.: Quellüftung, Forschungsbericht Nr. 522, Klimatechnisches Laboratorium Betzdorf, Heinrich Nickel GmbH, Klima- und Lufttechnik.

3- Heiselberg, P. & M. Sandberg: Convection from a Slender Cylinder in a Ventilated Room, RoomVent-90, Oslo, Norway, 1990.

4- Holmberg, R.B. et Al.: Inhalation Zone Air Quality Provided by Displacement Ventilation, RoomVent-90, Oslo, Norway, 1990.

5- Kegel, B. & U.W. Schulz: Displacement Ventilation for Office Buildlings, 10th AIVC Conference on Progress and Trends in Air Infiltration and Ventilation Research, Espoo, Findland, Sept. 25-28, 1989.

6- Kofoed, P. & P.V. Nielsen: Thermal Plumes in Ventilated Rooms - An Experimental Research Work, 3rd Seminar on Silesian Technical University, Gliwice, Poland 1988. Also published in Indoor Environmental Technology, paper no. 7, ISSN 0902-7513 R8833, 1988.

7- Kofoed, P. & P.V. Nielsen: Thermal Plumes in Ventilated Rooms - Measurements in Stratified Surroundings and Anlaysis by Use of an Extrapolation Method, RoomVent-90, Oslo, Norway, 1990.

8- Kofoed, P.: Thermal Plumes in Ventilated Rooms, Ph. D. Thesis, University of Aalborg, Denmark, 1991.

9- Mierzwinski, S.: Air Motion and Temperature Distribution Above a Human Body in Result of Natural Convection, A4-series no. 45, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1981.

10- Mundt, E.: Temperaturgradienter och Konvektionsflöden vid Deplacerende Ventilation, Ph.D. Thesis, KTH, Installationsteknik, Meddl. nr. 16., Sweden, 1991.

11- Popiolek, Z.: Problems of Testing and Mathematical Modelling of Plumes Above Human Body and Other Extensive Heat Sources, A4-series no. 54, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1981.

12- Rouse, H., C.S. Yih & H.W. Humphreys: Gravitational Convection from a Boundary Source, Tellus, 4, pp. 201-210, 1952.

13- Schmidt, W.: Turbulente Ausbreitung eines Stromes erhitzter Luft, Z. angw. Math. Mech., Bd. 21, Nr. 5 & 6, Okt. & Dez. 1941.

14- Skistad, H.: Fortrengningsventilasjon i Komfortanlegg med Lavimpuls Lufttilförsel i Oppholdssonene, Norsk VVS Teknisk Forening, 1989.

15- Skåret, E.: Ventilation by Displacement - Characterizing and Design Implications, Ventilation '85 edited by H.D. Goodfellow, Elsevier Science Publishers B.V., Amsterdam, 1986.