Air Distribution in Rooms with Ceiling-mounted Obstacles and Three-Dimensional Isothermal Flow

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INTRODUCTION

The air supply openings in ventilated rooms are often placed close to the ceiling, fig. 1. A recirculating flow is generated in the room, and the region between the ceiling and the occupied zone serves as an entrainment and velocity decay area for the wall jets. Ceiling-mounted obstacles may disturb this flow and, in particular, certain dimensions and positions of the obstacles cause a downward deflection of the jets into the occupied zone resulting in reduced thermal comfort for the inhabitants.

Experimental investigations of the influence of ceiling-mounted obstacles have been reported by e.g. Regenscheit (1), Majerski (2), Söllner & Klinkenberg (3), Holmes & Sachariewicz (4) and Schwenke (5). The experiments of Regenscheit, Majerski and Schwenke were made in model rooms with isothermal two-dimensional flow and those of Söllner & Klinkenberg and Holmes & Sachariewicz were made in full-scale rooms under non-isothermel and isothermal conditions, respectively. The flow was only quasi two-dimensional in the experiments of Söllner & Klinkenberg because the width of the supply opening was small compared to the room, while the experiments of Holmes & Sachariewicz were made under boundary conditions giving a fully two-dimensional flow. Recent papers by Nielsen (6) and (7) have shown the influence of a ceiling-mounted obstacle on the flow in different model and full-scale rooms under isothermal and non-isothermal conditions and model experiments in two-dimensional isothermal flow, respectively.

This paper presents results obtained with three-dimensional, isothermal flows in a model room having a circular supply opening (nozzle) located in the end wall close to the ceiling in the symmetry plane of the model. The first part of the paper deals with non-deflected flow and demonstrates the influence of the Reynolds number and the influence of ceiling-mounted obstacles on the penetration depth in long rooms. Some examples of velocity distribution in the wall jet and flow in the occupied zone are then demonstrated. The second part of the paper determines the critical dimensions giving a deflection of the supply jet into the lower part of the room (occupied zone).

AIR DISTRIBUTION IN A ROOM WITH NON-DEFLECTED FLOW

The wall jet has a limited penetration into a deep room. Entrainment implies that the air must be led back along the floor and this will disperse the jet. The penetration x_{re} is defined as the distance from the wall with the nozzle to the stagnation point where the flow diverges as indicated in fig. 1.

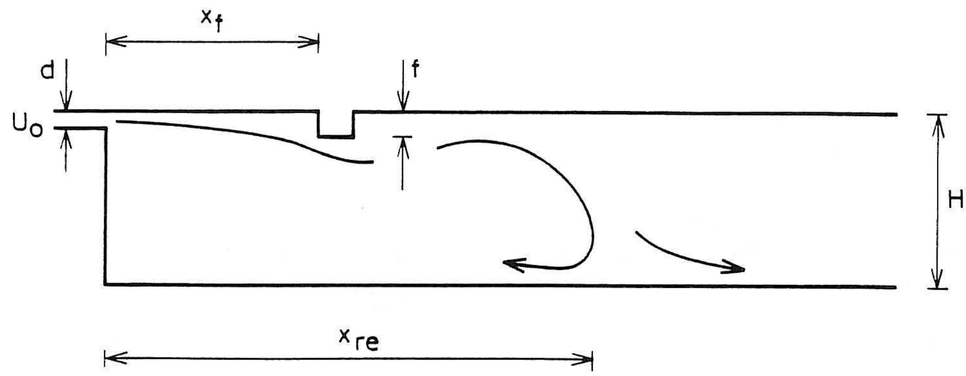

Fig. 1. The geometrical parameters describing the three-dimensional flow in a deep room.

Dimensional analysis shows that the flow is fully described by the geometrical parameters the Reynolds number Re and the boundary conditions, see ref. (8).

The penetration depth can thus be described by

$$\frac{x_{re}}{H} = \text{func}\left(\frac{H}{d}, \frac{f}{d}, \frac{x_f}{d}, \text{Re}\right) \tag{1}$$

where three of the variables on the right hand side represent the geometry normalized by the diameter of the supply nozzle d. The Reynolds number is given by

$$\text{Re} = \frac{U_o d}{\nu} \tag{2}$$

where U_o and ν are supply velocity and kinematic viscosity, respectively.

Fig. 2 shows the results of model experiments where the flow and the stagnation point are determined by a flow visualization technique. The penetration depth x_{re}/H is given for different f/d and different Reynolds number at a constant location of the obstacle and constant nozzle diameter (x_f/d = 16,7 and d/H = 0.03).

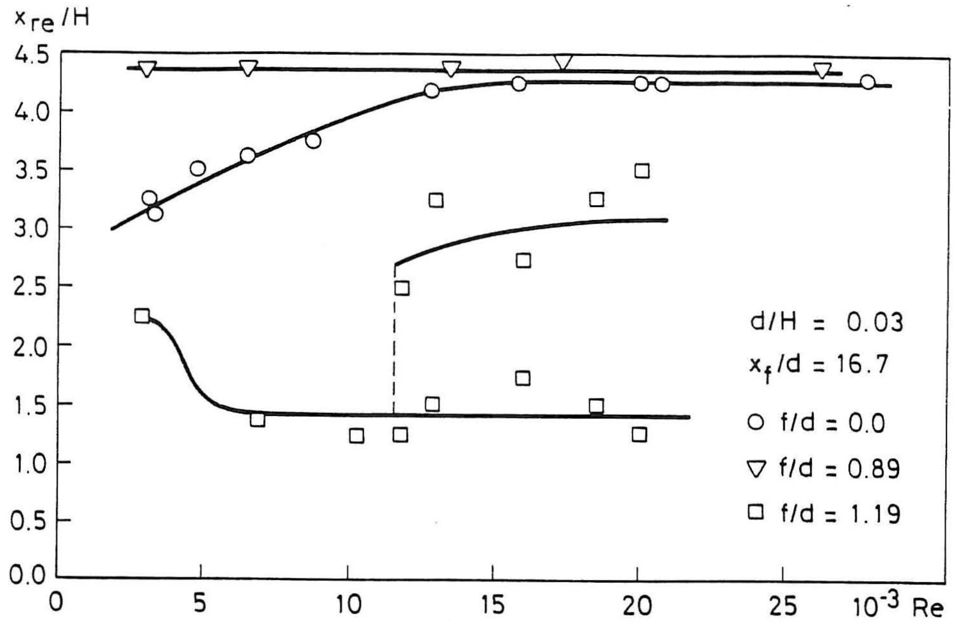

Fig. 2. Penetration depth versus Reynolds number in rooms with and without ceiling-mounted obstacles.

It may be shown that the normalized flow and the normalized velocity distribution in ventilated rooms are independent of the Reynolds number at fully developed turbulent flow, see (8). Fig. 2 shows that the normalized flow expressed by the penetration depths x_{re}/H is independent of the Reynolds number for Re $\geq$ 14000 and all further flow visualization tests are made at the Reynolds number Re = 14000. Velocity measurements are all made at a Reynolds number of Re = 22000.

Fig. 2 shows the penetration depth without an obstacle and with the obstacles f/d = 0.89 and f/d = 1.19. A small obstacle may increase the penetration depth while a larger obstacle (fx f/d = 1.19) may reduce the penetration depth and establish a flow with two steady solutions, a deflected and a non-deflected flow. This situation will be further discussed in the next chapter.

Fig. 3 shows the penetration depth x_{re} normalized with $\sqrt{A}$ where A is the end wall area (A = H×W) in a deep room without obstacles. It is obvious that the penetration depth depends on the cross-sectional area of the room (which is also the cross-sectional area of the wall jet flow and the entrainment flow), but the normalized value is rather independent of the height-to-width ratio of this area and rather independent of the relative supply area $d/\sqrt{A}$.

The penetration depth is a significant parameter in the dis-

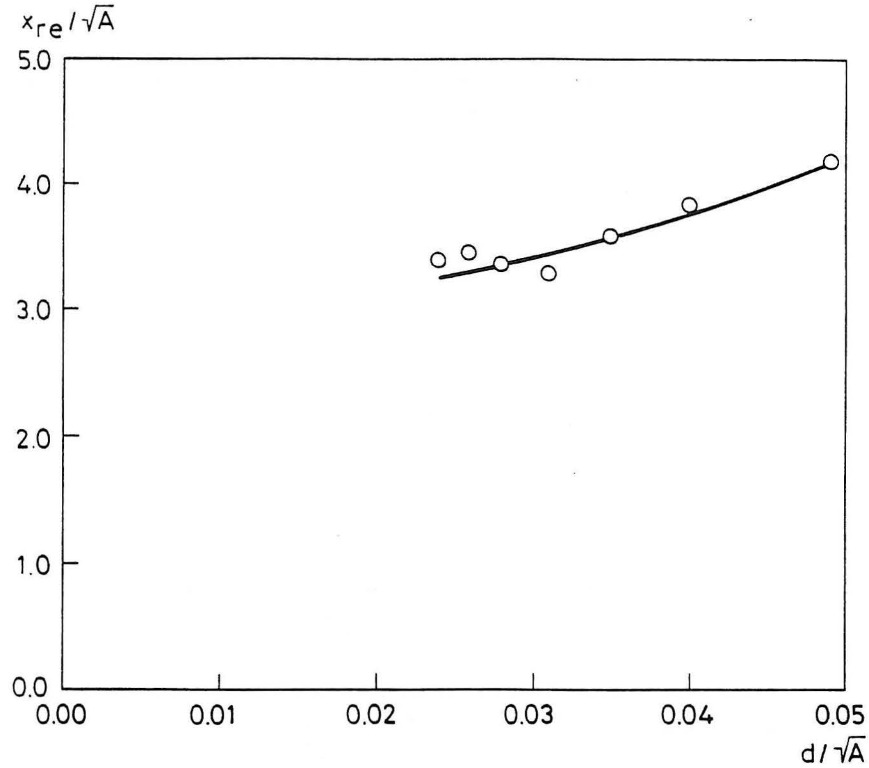

Fig. 3. Penetration depth for different supply areas $d/\sqrt{A}$.

cussion of room air distribution. The velocity is very low at distances from the supply opening exceeding the penetration depth, while the velocities are high at distances less than the penetration depth because large volumes of air are set into motion by the entrainment in the wall jet below the ceiling. A room air supply system shall always be designed in such a way that the ventilated section L is shorter than a calculated penetration depth x_{re} at isothermal flow. This would, for example, be ensured in the room in fig. 1 by locating a second set of ceiling-mounted supply openings close to the stagnation point.

The maximum velocity in the occupied zone is one of the important parameters in the design of an air distribution system and it has been discussed in detail in reference (9). A ceiling-mounted obstacle makes the design procedure complicated. A downward deflection of the jet, shown as situation B in fig. 6, will give rise to high velocities in the occupied zone and should normally be avoided by a proper choise of the geometrical parameters, as discussed later. This section discusses the influence of the obstacle in the situation where the flow generates a recirculating movement in the whole room (type A in fig. 6).

As discussed in connection with eq. (1) it is possible to write

$$\frac{U_{rm}}{U_o} = \text{func} \left(\frac{f}{d}, \frac{x_f}{d}, \frac{H}{d}, \frac{L}{H}\right) \tag{3}$$

where U_{rm} is the maximum reverse velocity. The velocity U_{rm} is located close to the floor at a distance of 1/2 L to 2/3 L from the supply opening, and it will also be maximum velocity in the occupied zone in the normal situation where the jet below the ceiling and the area close to the end wall opposite the supply opening are excluded from the occupied zone.

The influence of an obstacle may be deduced from fig. 4. Measurements in the wall jet show a velocity distribution which is inversely proportional to the distance x both in the case without and in the case with an obstacle (the slope of the curves in fig. 4 is equal to -1.0), but the velocity level is

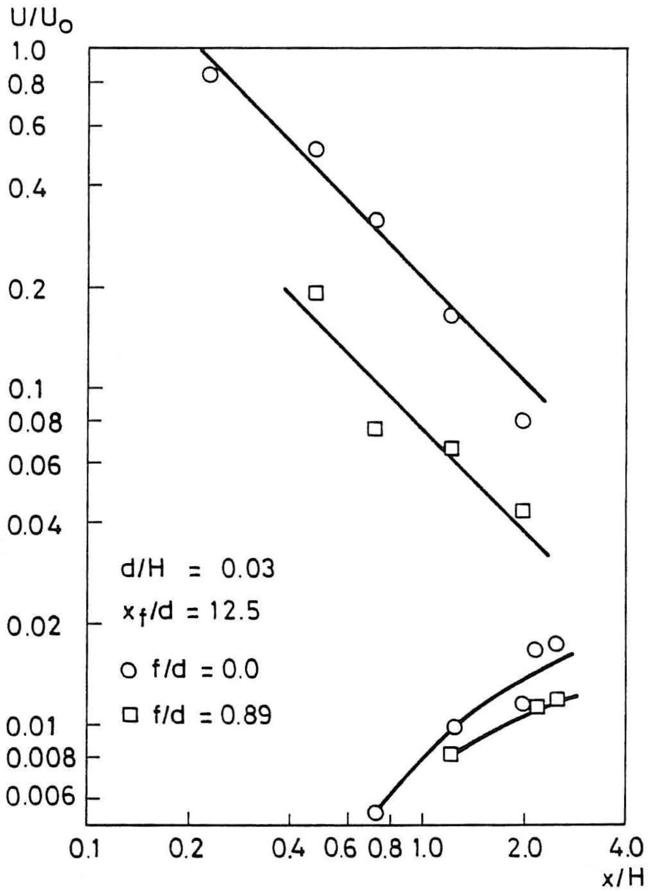

Fig. 4. Maximum velocity in wall jet and maximum reverse velocity in the occupied zone in a room with and without a ceiling-mounted obstacle.

reduced in the wall jet when it passes the obstacle at x_f/H = 0.38. This velocity reduction is present in the reverse flow in the lower part of the model as indicated in fig. 4, which also shows the reverse velocity distribution. The maximum velocity in the reverse flow (maximum velocity in the occupied zone) U_{rm}/U_o is reduced by 30% by the obstacle introduced in fig. 4.

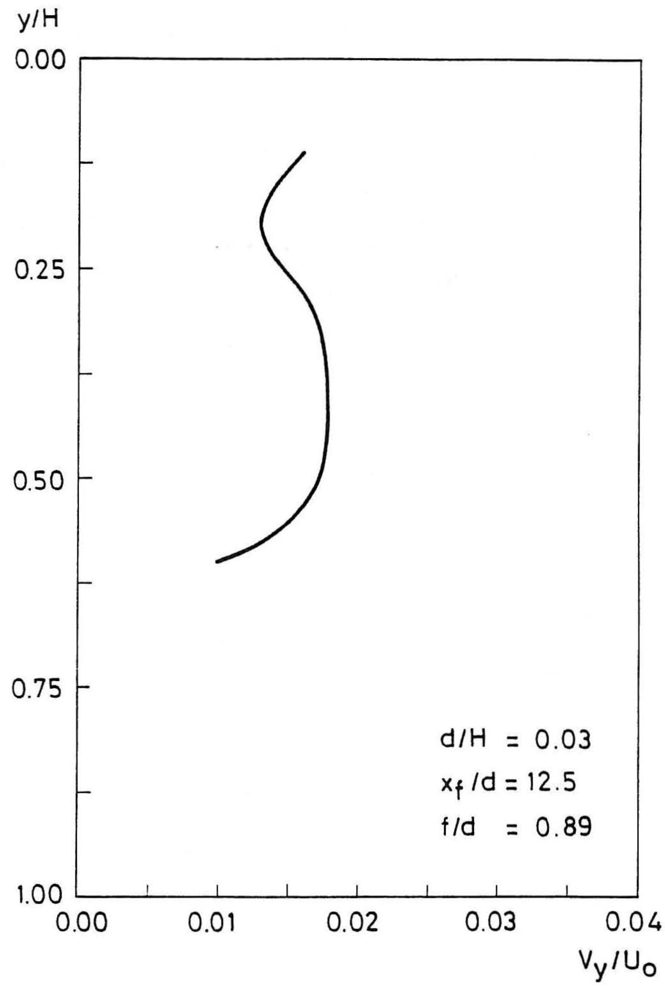

Fig. 5. Cross flow introduced in a room with three-dimensional flow and ceiling-mounted obstacle.

Further, the obstacle will introduce a cross flow in the model which may influence the air movement in the occupied zone. There will be cross flow in front of and parallel to the obstacle. It moves away from the symmetry plane down along the side walls into the occupied zone in the area below the obstacle. Fig. 5 shows as an example the maximum velocity of the cross flow V_y in the y-direction for f/d = 0.89 and x_f/d = 12.5.

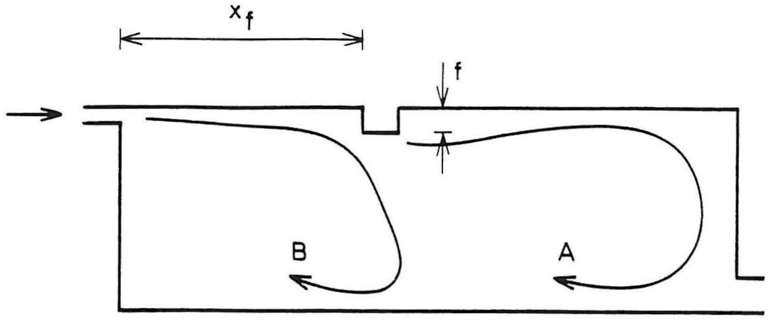

Fig. 6. Different steady state solutions for the three-dimensional flow pattern under isothermal conditions. Flow of type A is obtained for heights of the obstacle smaller than a critical value f_c.

Experiments show that depending on the governing parameters, the jet may either pass the obstacle and give rise to a recirculating flow in the whole room, situation A in fig. 6, or be deflected and result in situation B with locally higher velocities in the occupied zone. Both flow patterns may be steady solutions in a narrow range of parameter combinations as shown in fig. 2. Isothermal flow at high Reynolds numbers is fully described by boundary conditions at the supply opening and the geometrical parameters of the room (8). It is therefore sufficient to describe the preferred situation for a given air terminal devise by determing the critical height of the obstacle below which the flow is of type A for given values of the other geometrical parameter.

$$\frac{f_c}{d} = \text{func}\ (\frac{x_f}{d}, \frac{d}{H}) \tag{4}$$

Fig. 7 shows the dependence of the height f_c on the distance between the supply opening and obstacles for different room heights H. The height of the wall jet is increasing linearly from a point close to the supply opening and it should therefore be expected that f_c is a linearly increasing function of x_f. The figure shows this effect at small lengths, x_f, but f_c obtains a maximum value further downstream in the model.

Measurements on a wall jet from a nozzle generated in a large laboratory room (W×H equal to 7×3 m) are also given in fig. 7, reference (10). The measurements show the expected linear relationship between f_c and x_f, and they explain the decreasing

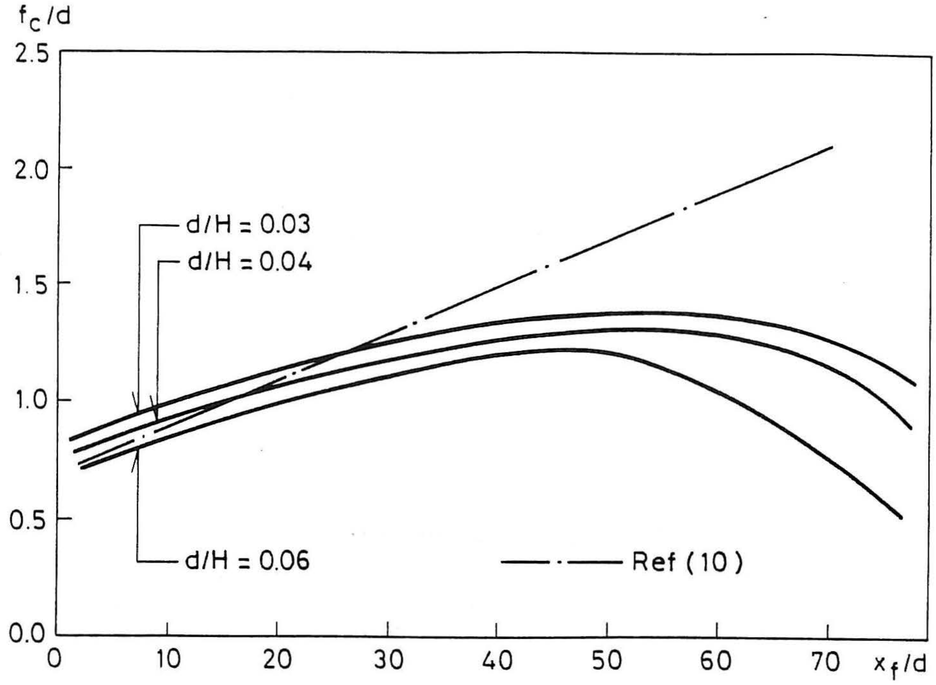

Fig. 7. Dependence of critical height f_c on the distance between obstacle and supply opening x_f.

f_c-value in the model experiments for high x_f as the influence of the room height in the model. Influence from room height has also been reported by earlier measurements, references (6) and (7).

The influence of room length or location of end wall has not been considered in equations (1) and (4). The end wall location in the experiments shown in fig. 2, 3, 4, 5 and 7 is $x/d = 150$, and it has not been possible to show any significant influence in rooms which are long compared to x_{re} and x_f.

The thickness δ of wall jets from different types of air terminal devices is given in fig. 8 (δ is defined as the height to the velocity $U_x/2$ where U_x is the maximum velocity in the profile). The figure shows results for two-dimensional flow from slots, linear ceiling diffusers, different types of nozzles and end wall mounted grilles with different adjustment of blades. The critical height f_c for two-dimensional flow from a slot (4), flow from linear ceiling-mounted diffusers (3) and (11), flow from a nozzle (10), and flow from end wall mounted grilles with different adjustment of blades (11), are also given in fig. 8 for rooms of large height and length. It is seen from the figure, that the thickness δ and the critical height f_c are linear functions of the distance x. It is also shown that f_c seems to be a constant fraction of δ in the area where the wall jet is fully developed ($x > 2$ m). The variation of f_c is more compli-

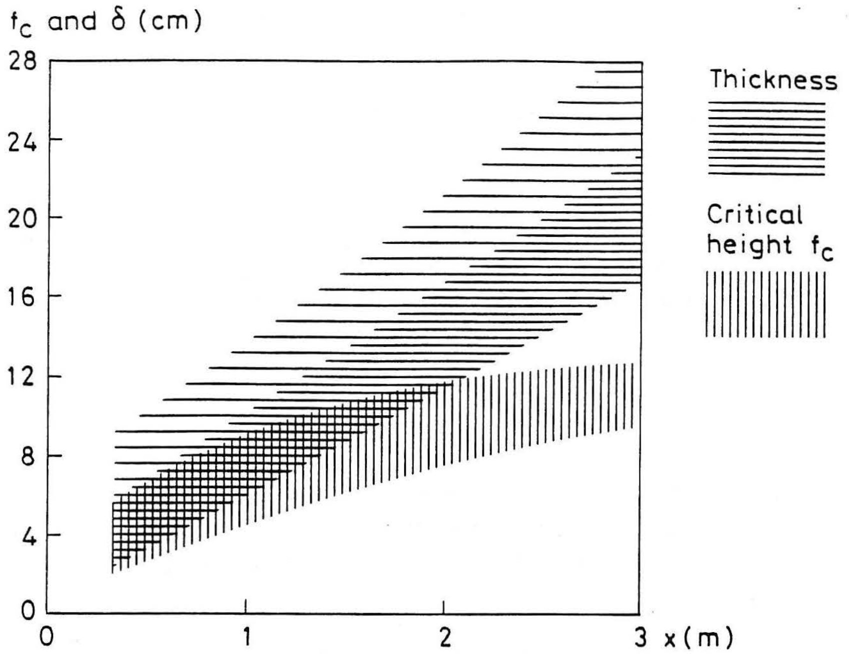

Fig. 8. Wall jet thickness δ and critical height of obstacle f_c versus distance from supply opening for different air terminal devices. Reference (3), (4), (10) and (11).

cated close to the supply opening, where height of opening and directions of the jet are some of the relevant parameters.

It will often be impossible to use the results from fig. 8 in rooms of normal height and length. It may for example be shown that an obstacle height of 10 cm very often generates a deflection in a room of the dimensions H, W and L equal to 2.4, 3.6 and 5.4 m, reference (11). Reference (6) shows the same trend with deflection at light fittings with the height of 10 cm.

CONCLUSIONS

Ceiling-mounted obstacles will influence the isothermal three-dimensional flow from an end wall mounted nozzle even in such cases where the wall jet passes the obstacle without a permanent deflection. The penetration depth of the jet in a deep room can be sligthly increased. The maximum velocity in the jet may be reduced considerably as well as the maximum velocity in the occupied zone.

The obstacle may generate a downward cross flow into the occupied zone in situations where the primary jet is non-deflected. This flow could result in draught at high supply velocities.

In particular, ceiling-mounted obstacles may deflect the three-dimensional isothermal wall jet down into the occupied zone. Model tests show that the critical height of the obstacle is a function of nozzle dimension, distance from supply opening and height of the room.

The critical height of the obstacle may be a linear function of distance from the supply opening in rooms with large dimensions. However, measurements in a room of normal dimensions do not show this simple relation and an obstacle height of 10 cm will often generate permanent deflection.

REFERENCES

(1) Regenscheit, B., Modellversuche zur Erforschung der Raumströmung in belüfteten Räumen (Measurements of room air distribution in ventilated rooms by model experiments), Staub, No. 1, 1964.

(2) Majerski, S., The air distribution in auditoriums generated by the ventilation system (in Polish), Diss. T.U. of Silesia, 1970.

(3) Söllner, G., and K. Klinkenberg, Leuchten als Störkörper im Luftstrom (Lighting fixtures as obstacles in air flow), Heizung Lüftung/Klimatechnik Haustechnik, 23, No. 4, 1972.

(4) Holmes, M.J. and E. Sachariewicz, The effect of ceiling beams and light fittings on ventilating jets, Laboratory report No. 79, HVRA, 1973.

(5) Schwenke, H., Das Verhalten ebener horizontaler Zuluftstrahlen im begrenzten Raum (The behaviour of two-dimensional horizontal supply jets in a short room), Diss. T.U. of Dresden, 1973.

(6) Nielsen, P.V., The influence of ceiling-mounted obstacles on the air flow pattern in air-conditioned rooms at different heat loads, Building Services Engineering Research & Technology, Vol. 1, No. 4, 1980.

(7) Nielsen, P.V., Air diffusion in rooms with ceiling-mounted obstacles and two-dimensional isothermal flow, 16th International Congress of Refrigeration, Commission E1, International Institute of Refrigeration, Paris, 1983.

(8) Nielsen, P.V., Flow in air conditioned rooms (English translation of Ph.D. thesis from the Technical University of Denmark, 1974), Danfoss A/S, Denmark, 1976.

(9) Nielsen, P.V., Bestimmung der maximalen Luftgeschwindigkeit in der Aufenthaltszone eines klimatisierten Raumes (Calculation of the maximum air velocity in the occupied zone of an air-conditioned room), Heizung Lüftung/Klimatechnik Haustechnik, No. 9, 1980.

(10) Egedorf, M. and M.H. Jensen, Private communication, Institute og Building Technology and Structural Engineering, University of Aalborg, 1986.

(11) Jensen, M.K., H.H. Larsen and J.B. Madsen, Private communication, Institute of Building Technology and Structural Engineering, University of Aalborg, 1987.

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