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PAPER NO. 46

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The Effect of Obstacles on the Boundary Layer Flow at a Vertical Surface

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The Effect of Obstacles on the Boundary Layer Flow at a Vertical Surface

ABSTRACT

Glazed facades may cause thermal discomfort due to downdraught. Convectors placed close to the facade can prevent downdraught but cause an increase in the energy consumption. The objective of the research has been to investigate if the structural system of a glazed facade can be used to reduce downdraught and to avoid thermal comfort problems in the occupied zone.

The effect of large obstacles on a cold boundary layer flow has been investigated for different temperature differences between a cold surface and the room air, different distances between the obstacles and different sizes of the obstacles.

The effect of the obstacles on the boundary layer flow depended on the characteristics of the flow and of the sizes of the obstacles. With turbulent flow and an obstacle larger than the boundary layer thickness the boundary layer flow separated from the surface and a new boundary layer was established below the obstacle. The risk of thermal discomfort due to downdraught was reduced considerably.

INTRODUCTION

Glazed facades and atria have become popular as architectural features in building design. They are found in manytypes of buildings e.g. office buildings, hotels, hospitals and shopping malls. In cold regions they give people the opportunity to perform their daily activities in a naturally lit environment, away from the negative effects of a long and cold winter. The use of an atrium can create a thermally compact building where heat loss from the parent building is reduced and passive solar energy gained in the atrium is utilized. Furthermore, both glazed facades and atria can improve the usability of daylight by allowing it to penetrate deep into the building in the adjacent rooms and thereby reduce the need for electrical lighting.

In winter, however, glazed surfaces in buildings in cold regions are often the cause of thermal discomfort partly due to cold radiation effects and partly due to downdraught problems caused by cold natural convective flows along the surface. For glazed surfaces the most critical problem is downdraught.

A reduction of the cold natural convective flow can be obtained by increasing the surface temperature of the glass or by neutralizing the flow by a warm air flow in the opposite direction. The surface temperature can be increased passively by reducing the heat loss through the window (more layers of glass, gas filling, low emission glass). The surface temperature can be increased actively by heating the surface with warm air from convectors close to the surface, alternatively by radiant heating or by electrical heating of the glass. The cold convective air flow can be neutralized with a warm air curtain rising from convectors or supplied through ventilation slits. Common to all the active measures to avoid downdraught is the fact that they increase the energy consumption because of the increase of the interior surface temperature and because the convectors etc. may be active also in periods when general room heating is not needed.

At low windows downdraught problems can be avoided passively by reducing the heat loss through the window. Heiselberg (1994) has investigated the draught risk in the occupied zone from low window surfaces. For an aceptable percentage of dissatisfied of 15%, because of downdraught it was shown that a double glazed window will cause downdraught problems in at least 15% of the year in Denmark, and for window heights of more than 1 m the percentage will be even higher. On the other hand, a double glazed window with low emission glass and argon filling will not cause any downdraught problems for a normal window height of 1.25 m. For window heights equal to normal room height the use of a trible glazed window with low emission glass and argon filling will prevent discomfort due to downdraught in the occupied zone. So, for window heights below normal room height it is possible to prevent downdraught problems if the right window type is selected. However, for window heights of more than normal room height downdraught problems cannot be prevented by selecting window types with a low heat transfer coefficient and therefore some kind of active measure will be necessary.

The objective of this research is to investigate if the structural system of a glazed facade or an atrium can be used to reduce downdraft and to avoid thermal comfort problems in the occupied zone. Thereby, the initial costs of e.g. a convector or ventilation system could be saved and the energy consumption could be reduced in the future.

DESCRIPTION OF PRINCIPLE

In ventilated rooms the air inlet device is often placed close to the ceiling. The inlet air forms a wall jet. This jet may be disturbed by ceiling-mounted obstacles such as light fittings or ceiling beams which in some cases might cause the air jet to be deflected into the occupied zone. Several authors (Söllner and Klinkenberg 1972, Holmes and Sachariewicz 1973, Nielsen 1980) have presented experimental results which describe the influence of ceiling-mounted obstacles and they have found the critical height of the obstacle at which the deflection takes place. The velocity level in the jet will be reduced after the jet has passed the obstacle, and if the height of the obstacle is lower than the critical height the jet will reattach to the ceiling.

The same phenomenon may appear for the boundary layer flow at a vertical wall with obstacles. At glazed facades the beams in the structural system will act as large obstacles for the boundary layer flow. Depending on the width of the obstacle different flow conditions can be expected to occur as shown in principle in figure 1. When the width of the obstacle is smaller than a critical width the boundary layer flow reattaches to the surface after it has passed the obstacle. The velocity will, however, be reduced and therefore smaller velocities and an improvement in the thermal comfort can be expected in the occupied zone compared with the situation with a plane

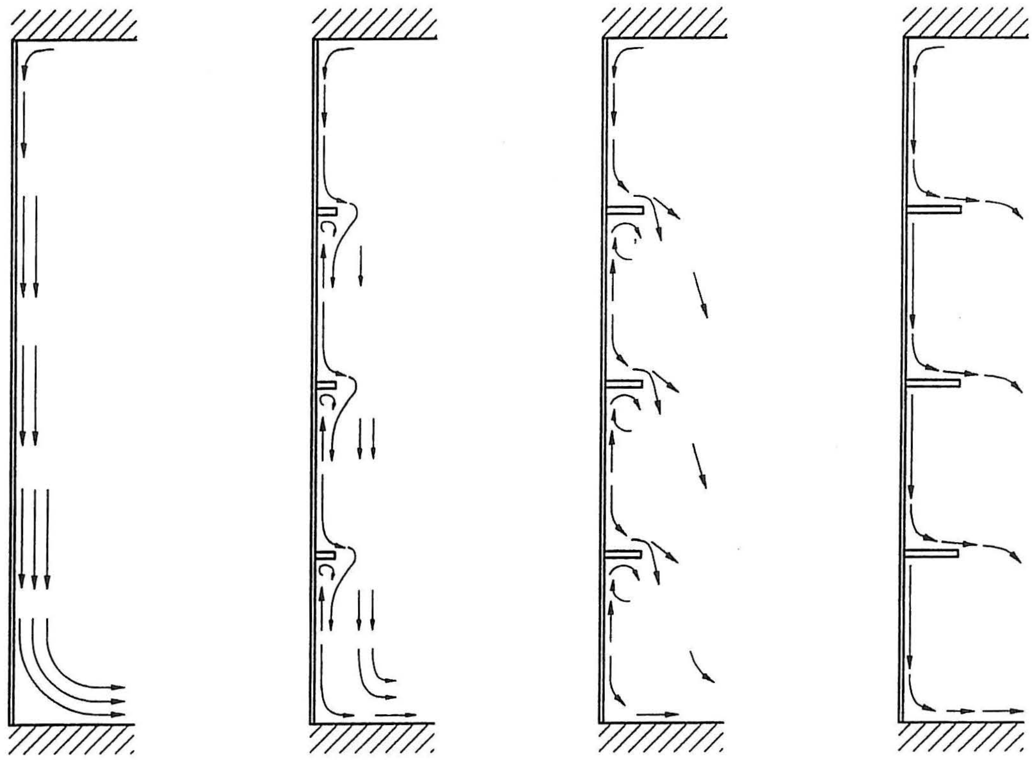

Figure 1. Principle of flow conditions at a cold vertical wall with different sizes of obstacles.

surface. When the width of the obstacle is larger than a critical width the boundary layer flow will separate from the surface after it has passed the obstacle and a new boundary layer flow will be established below the obstacle. The separated air flow will flow into the room probably acting like some kind of cold air jet. In this way a high glazed facade can be expected to act as a combination of smal individual parts on top of each other. The top parts supply cold air to the room above the occupied zone and the risk of downdraught in the occupied zone is only determined by the flow conditions at the lowest part of the facade.

LABORATORY SET-UP

The experiments were conducted in a well-insulated room without mechanical ventilation with the dimensions L × W × H = 4.6 m × 3.0 m × 3.3 m. The room was divided into a cold and a warm section by an insulated wall with a window (W × H = 1.2 m × 3.3 m) placed in the middle. On the cold side of the window it was possible to cool down the room to approximately -10°C and on the warm side heating could be supplied and a normal room temperature maintained. The warm section of the room was 3.7 m long, and it was in this part the measurements were carried out. This situation is eqvivalent to a typical occupied room in a heated building during winter, where the exterior walls and especially the windows are cooler than the room air and the interior surfaces.

The experiments were concentrated on the physical impact of rectangular obstacles (in the form of baffle plates) on the boundary layer flow close to the cold window. In the experiments temperatures were measured at several heights in the room air, on the window pane as well as on the other surfaces. The measuring equipment was thermocouples (type K) and a data logger (type Fluke Helios 2287 A) connected to a PC. The thermocouples were calibrated to an accuracy of ±0.15°C in the range 10°C - 30°C.

Special care was taken to ensure two-dimensional flow at the window. This was done by placing plywood sheets at each side of the window, perpendicular to the window and extending 1.2 m into the room. In each experiment, only one obstcale was used, which was placed 1 m above the floor. The flow around the obstacle was visualized with white smoke, which was supplied under isothermal conditions and with a very low impulse, so it disturbed the flow pattern to a very small extent. The flow pattern was recorded with a video camera.

The room air temperatures and the window surface temperatures were chosen together with the height of the window over the obstacle to produce boundary layer flows at different Grashof numbers. To be able to vary the height of the window an artificial "ceiling" was placed between the plywood sheets. For each Grashof number several obstacles with different widths were tried, the widths varying between 0.05 m - 0.4 m.

MEASUREMENT RESULTS

In most situations the flow around an obstacle will follow one of two characteristic patterns: Either the flow will reattach to the window quickly after it has left the edge of the obstacle, creating a recirculating flow immediately under the obstacle, or the flow will separate completely from the window, following a steep downward curve while mixing with the room air. An intermediate pattern can be observed where the flow is unstable and neither separates properly nor creates the characteristic recirculation zone. This intermediate flow pattern will occur at a certain combination of the Grashof number and the width of the obstacle, see figure 1. This width was defined as the critical width $\mathbf{w}_{cr}$ for that particular Grashof number. This is illustrated by an example in figure 2 where $Gr_h = 5.5 \cdot 10^9$. Experiments were conducted at eleven different combinations of temperature differences, $\Delta\theta$, and window heights, h, producing Grashof numbers varying from laminar ($Gr_h = 6.9 \cdot 10^8$) to fully turbulent ($Gr_h = 1.7 \cdot 10^{10}$). For each Grashof number different sizes of obstacles were used to find the critical width. This gave a total number of experiments of 55. Critical widths were found for all Grashof numbers except for the most laminar case, where w_{cr} was very large and of no practical interest. The critical width proved to be greatly dependent on the Grashof number. In the case of laminar flow, $Gr_h <$ approx. $2 \cdot 10^9$ Cheesewright (1982), the flow was very reluctant to separate and relatively large critical widths were found. With increasing Gr_h, w_{cr} decreased until fully developed turbulence was reached at $Gr_h > 1 - 1.6 \cdot 10^{10}$ (Cheesewright 1982), where the critical width is approximately equal to the thickness δ of the boundary layer calculated as:

$$\delta = 0.1 \cdot \Delta\theta^{\,0.1} \cdot h^{\,0.7} \qquad (1)$$

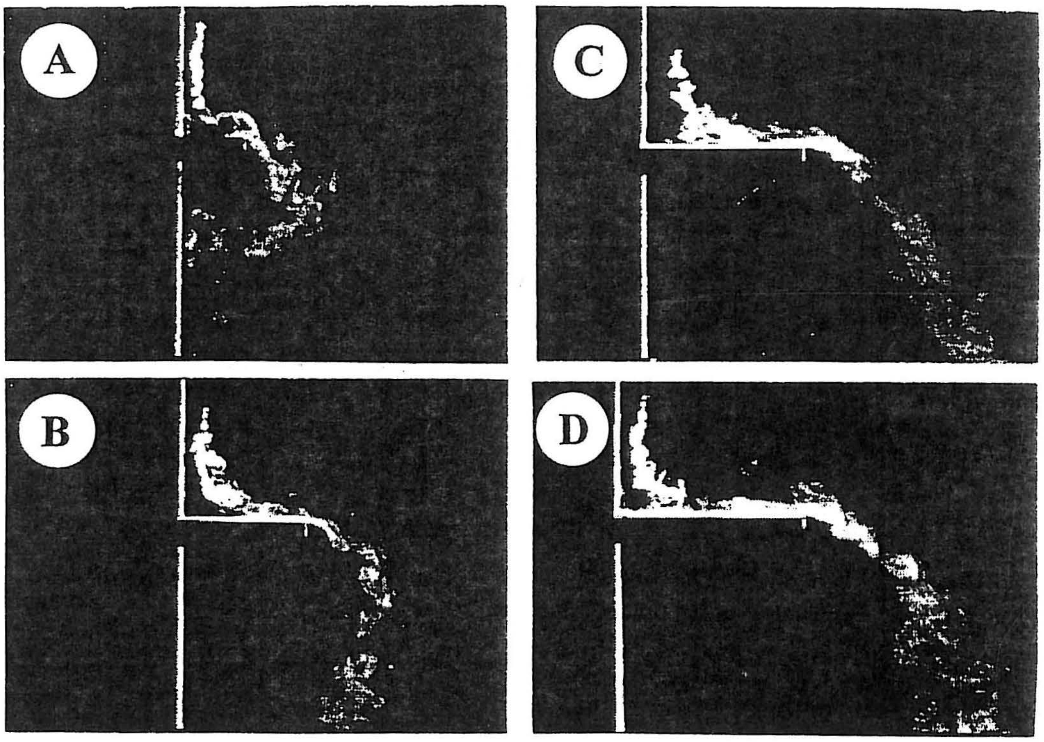

Figure 2. Photos showing how an increasing width of the obstacle changes the air flow pattern at a Grashof number of $Gr_h = 5.5\ 10^9$. The width of the obstacle is A: w = 0.1m; B: w = 0.2 m; C: w = 0.25 m and D: w = 0.3 m.

It is very likely that the critical width will increase beyond the values shown in figure 3 if the Grashof number is increased beyond $1.7 \cdot 10^{10}$, but unfortunately it was not possible to test this with the existing test room. As the figure indicates there was some ambiguity as to the correlation of Gr_h and w_{cr}, in so far as experiments with nearly identical Grashof numbers could produce widely differing critical widths. This seems to be attributable to the temperature gradients in the test room and at the window. In experiments with a relatively large temperature difference ($\Delta\theta \sim 15°C$) measurements show a very evenly distributed temperature difference throughout the height of the room. In experiments with a small temperature difference ($\Delta\theta \sim 5°C$), measurements show a more unevenly distributed temperature difference, probably due to stratification effects. These differences in experimental conditions could be the cause of differences in the turbulence of the flow where a situation with an uneven distribution might create more turbulence.

This could explain the results in figure 3, where the experiments with $\Delta\theta \sim 5°C$ apparently reach fully developed turbulence before the experiments with $\Delta\theta \sim 15°C$.

The temperatures and the air velocities at the front edge of the obstacle were measured, the temperature with a very thin thermocouple and the air velocity with a slender hotwire anemometer. This was carried out as it was the opinion that these parameters might determine the flow pattern, which would be the case if the air leaving the edge of the obstacle behaved as a two-

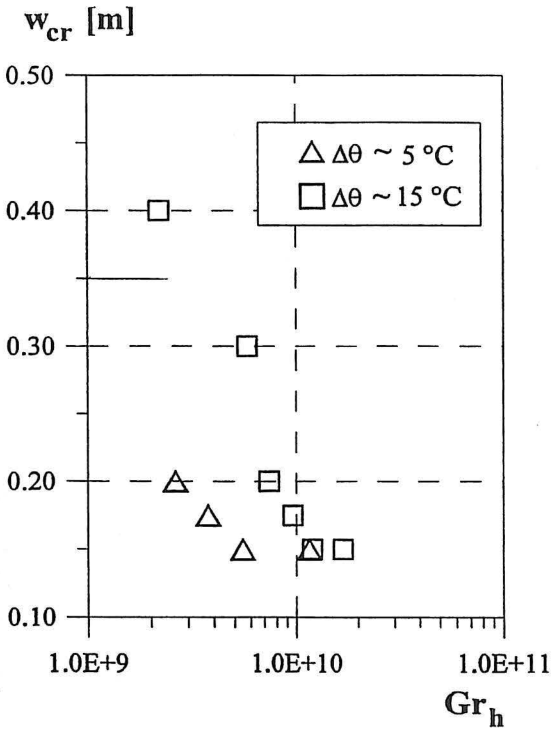

Figure 3. Critical width of the obstacle as a function of the Grashof number.

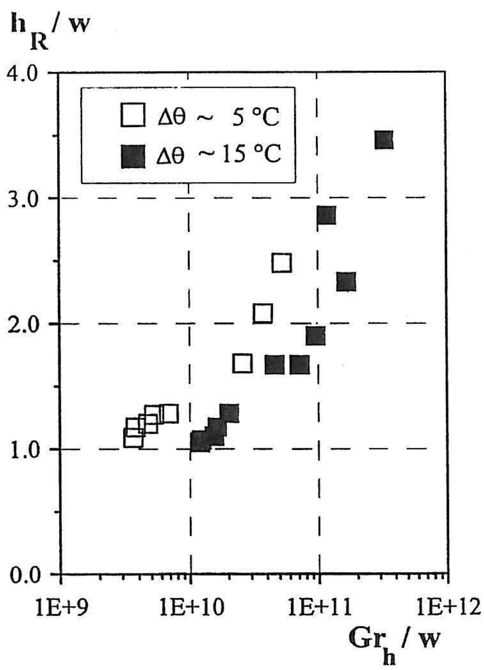

Figure 4. Length of recirculation zone as a function of the Grashof number and the width of the obstacle.

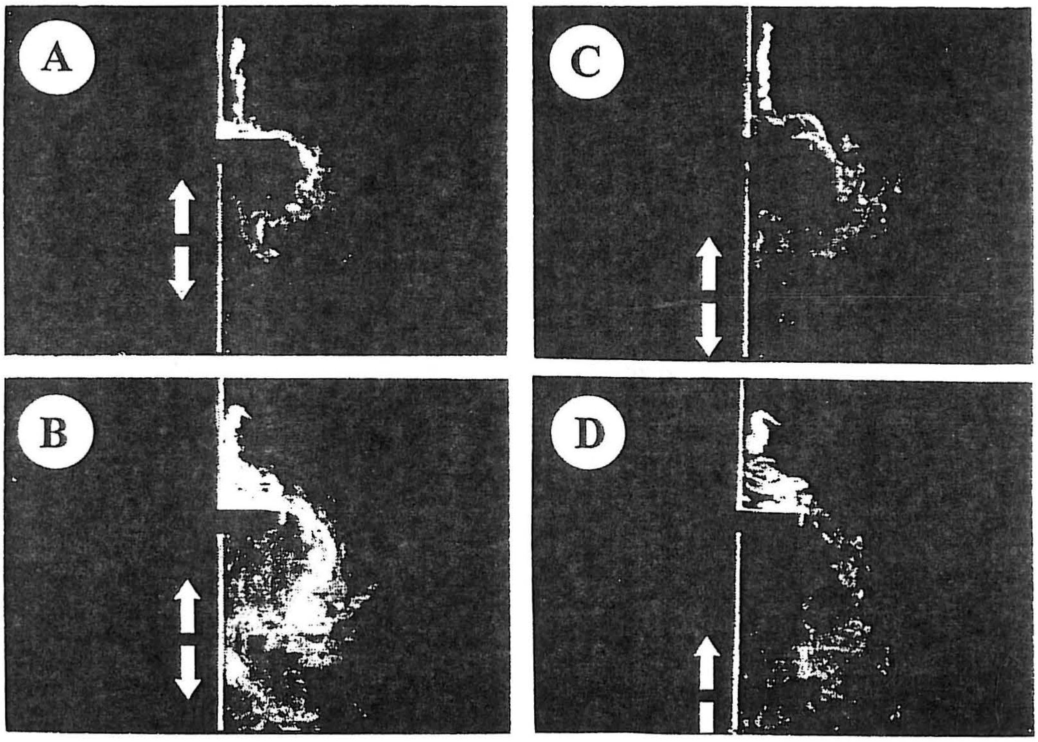

Figure 5. Photos showing how an increasing Grashof number increases the recirculation length at a width of the obstacle of w = 0.1 m. The Grashof numbers are A: $Gr_h = 6.85 \cdot 10^8$; B: $Gr_h = 2.59 \cdot 10^9$; C: $Gr_h = 5.30 \cdot 10^9$ and D: $Gr_h = 1.16 \cdot 10^{10}$.

dimensional jet. However, in all experiments with seperation the air flow followed the same trajectory independent on air velocity and temperature in the flow. The obstacle was located only 1 m above the floor and at this short distance the air flow path is likely to be affected by the deflection at the floor. Therefore, no conclusion can be drawn on how the trajectory will be in a room after separation.

For all situations with recirculating flow the height h_R of the recirculating zone was found on the video recording. For this purpose video recording proved to be superior to photography as the direction of the flow could be determined with much greater accuracy. The height of the recirculating zone h_R seems to be dependent on the Grashof number as well as on the width of the obstacle, see figure 4. The above mentioned differences between experiments with different $\Delta\theta$ are also apparent in this figure. For a given obstacle, h_R will not be smaller than the width of the obstacle. As Gr increases, h_R also increases. This is illustrated by an example in figure 5 where the width of the obstacle is kept constant at 100 mm. The physical explanation of this phenomenon probably has to do with the thickness δ of the boundary layer flow, which is a function of the Grashof number, rather than with the Grashof number itself. When $\delta/w > 1$ there will be a downward velocity composant outside the obstacle, which will elongate the recirculation zone.

CONCLUSION

The experiments have shown that it is possible to use the structural system of a glazed facade to separate the natural convective boundary layer flow from a cold surface. In this way a high surface acts as a combination of smal individual parts on top of each other where the top parts supply cold air to the enclosure above the occupied zone and where thermal comfort and the risk of draught in the occupied zone are only determined by the flow conditions of the lowest part of the facade. Fully turbulent conditions in the boundary layer flow are needed if the size of the obstacle should be kept reasonable. This means that the spacing between the obstacles should not be below 2 m.

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NOMENCLATURE

g	Gravitational acceleration, $g = 9.82$	(m/s^2)
Gr_h	Local Grashof number $Gr_h = g\ \beta\ \Delta\Theta\ h^3/\ \nu^2$	
h	Spacing between obstacles	(m)
h_R	Recirculation length (height) of flow behind obstacle	(m)
H	Surface height	(m)
w	Width of obstacle	(m)
w_{cr}	Critical width of obstacle	(m)
β	Volumetric expansion coefficient	(K^{-1})
δ	Boundary layer thickness	(m)
ν	Kinematic viscosity	(m^2/s)
$\Delta\theta$	Temperature difference between room air and surface	(°C)

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