#6222

"The PEARL" - A CASE STUDY

CARRYING AIR JETS AND AIR DISPLACEMENT PANELS USED IN THE PEARL

Dr. Oddur B. Björnsson and Gunnar Geirsson.
Fjarhitun hf Consulting Engineers
Reykjavík Iceland

SUMMARY

The latest addition to the skyline in Reykjavík, the capital city of Iceland, is the spectacular new 200 seat restaurant and conference building "The Pearl", owned and constructed by the Reykjavík Municipal Heating Service. The building is on top of six geothermal hot water storage tanks on the Öskjuhlíð hill in the centre of the city. The total volume of the building is 24 000 m^3 on six floors. The roof of the building is a near hemispherical glass dome of 1 720 m^2. Other glass surfaces have a total area of 280 m^2. The inside height of the building, which is open from the basement up to the top of the dome, is 28 m.

Cooling of the building during a sunshine load of 900 W/m^2 is provided by a ventilation system having a 24 m^3/s maximum air displacement capacity. On the fifth floor, directly under the glass dome, a revolving restaurant floor is surrounded by a 97 m long and 15 cm high vertical air displacement panels close to the floor. There are also pairs of linear diffusers and air nozzles on the top of the edge surrounding the outer circumference of the floor. The directing air jets help to carry the ventilation air into and above the seating area of the restaurant floor. The ventilation air from the basement, travels up through the open space to the top of the dome where it is exhausted through a number of roof vents.

The system was put through a tough test during the first summer of operation, which was one of the warmest in Iceland in a fifty year period. The air distribution technique adopted for the difficult dome area proved to be very effective.

INTRODUCTION

The "Pearl" Restaurant and Meeting Centre was inaugurated in June 1991. The building is on top of the 60 m high Öskjuhlíð hill in central Reykjavík and is owned by Hitaveita Reykjavíkur (the Reykjavík Municipal Heating Service). The "Pearl" gets it's name from the large glass dome which appears to sit on top of six hot water storage tanks, but in fact the dome is founded on concrete walls almost concentric with the the tanks. The tanks, which are a part of the Hitaveita's geothermal district heating system, are of 4 200 m^3 capacity each, arranged in a circle with a space of some 5 m between each two tanks. Glass facades, of almost 11 m in height between the tanks, form the outer boundaries of the ground floor of the building. The glass dome has the form of a sphere with a base diameter of 39 m. The height of the dome is 13 m and the radius of the sphere is 21 m. The volume under the dome is 9 000 m^3, and the total building volume is approximately 24 000 m^3. The dome and glass facades are made from hollow steel profiles through which warm water is passed for basic heating of the building.

The building has three main floors and a large basement with a conference room. The ground floor, of just under 1 000 m^2 at an elevation of 58 m, is used for exhibitions and large social gatherings. The fourth floor, of 1 000 m^2 is at 71.7 m elevation. Here is a caffeteria and the main kitchen. On the fifth floor, at 75.6 m, is a restaurant for 200 guests and a small kitchen. The restaurant seating area is on a 390 m^2 revolving floor, which rotates one revolution per hour for a round view of the capital. On top of the hot water storage tanks, level with the fourth floor, is a large outside observation platform for viewing the city of Reykjavík and it's surroundings. A bar is on the sixth floor.

THE VENTILATION SYSTEM

The building has two main primary air handling units (AHU's) for supplying fresh air for cooling and temperature regulation. The secondary supply system is of the variable air volume (VAV) type; medium pressure air is supplied in round ducts to VAV boxes, where the air quantity and temperature is regulated in sequence according to the indoor room conditions at any instant. The systems use fresh outdoor air only. The AHU's are interconnected on the discharge side, so that one of the two AHU's can operate the whole system temporarily, if the other is stopped for some reason. The maximum air quantity for cooling is 24 m^3/s, whereof about 17 m^3/s are discharged through eleven roof vents on the top of the dome. No fans are used in the roof vents, but a suitable positive static pressure is maintained in the building for driving the air out through the vents.

A special feature of the heating system is worth mentioning in connection with the ventilation system. As said before, the dome and facades are made from hollow steel profiles. Through the profiles, which are 140 x 80 x 6.3 mm, temperate water is circulated for heating and temperature equalization in the large open spaces. The maximum water temperature in the profiles is 38°C and the temperature difference is about 6°C. The overall heating effect is well over 100 kW. The total quantity of water in the profiles is 29 tonnes, and it takes 75 minutes to circulate the water. Temperature regulation is, therefore, rather slow, and the ventilation system must be used for accurate space temperature control.

AIR MOVEMENT

The ventilation air is introduced into the building mainly from the peripherial walls close to the glass facades and dome, but additional cooling effect is obtained on the top floor from air blown in from the central staircase and kitchen wall. A substantial quantity of air moves up through the open space in the centre of the building. The air, supplied to the basement and ground floor areas, travels up through the building where it mixes with the supply air which is introduced on the upper floors. All the air which is blown into the open spaces is discharged through eleven roof vents in the top of the dome, figure 1.

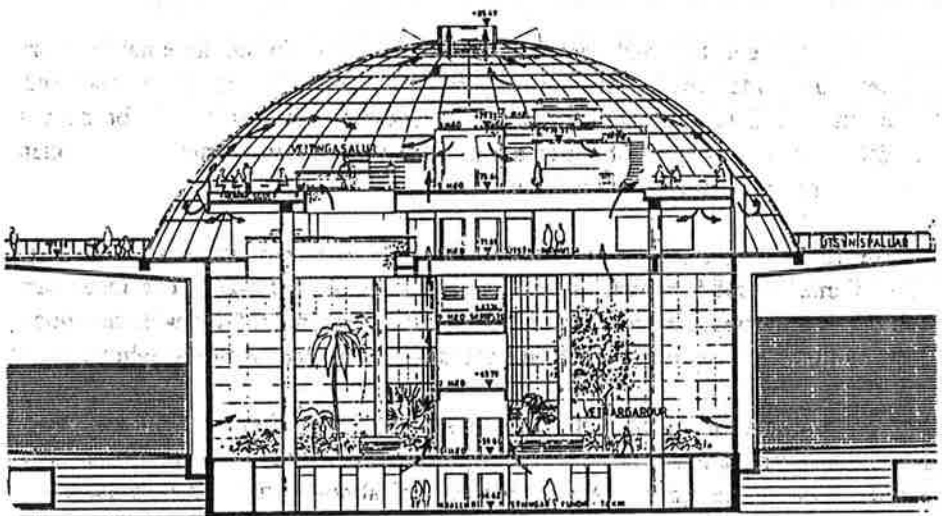

Fig. 1 Air movement

The vertical temperature gradient through the building can be quite high during a sunny day. The maximum design temperature on the ground floor is 24°C, 26°C on the fourth floor and 27°C on the top floor. The minimum room temperature on all floors is 21°C.

HEAT LOAD

The glazing in the dome and windows is silver coated and reflects around 78% of the oncoming sun radiation, i.e. only 22% of the heat penetrates the glass. The dayligth penetration is, however, 33%. The maximum external heat load from direct sunshine is approximately 900 W/m^2 at an angle of 49°. The area of the dome affected by heat from the sunshine is close to 60% of the total surface area of 1720 m^2, whereof around two thirds appertain to the top floor. The direct heat from the sunshine is generally highest at outside temperatures below 14 to 16°C, since at higher temperatures the sky is often overcast.

It is estimated that the heat which penetrates the glass surface from direct sunshine can be as high as 135 kW on the top floor and 70 kW on the fourth floor, but these spaces lie directly under the glass dome. On the ground floor the effect of direct sunshine through the vertical glass facades is much smaller, or no more than 20 kW.

COOLING AIR DISTRIBUTION

In order to meet the high heat load, and to maintain an acceptable room temperature under the dome, a flow rate of 16 m^3/s of cool air is required, based on a 10°C temperature increase. For example, air of 16°C will be heated to 26°C, which is close to the maximum room temperature. Internal heat gain has then, however, not been included.

On the fifth floor, the restaurant seating area is on a revolving floor of 10.6 m inner diameter and 5 m width surrounded by a 70 cm high wall. The inner part of the wall is integrated with the floor construction and rotates with the floor. The ventilation air is distributed into the space from the dome periphery.

The proximity of the people sitting by the surrounding wall enjoying the view and the relaxed atmosphere of the revolving floor restaurant, figure 2, posed some problems to the designers: A total air flow of almost 5 m^3/s at a temperature as low as 14°C needs to be introduced from the wall without disturbing the comfort of the guests. This, in addition to the air emerging from the lower floors, had to be directed in such a manner as to create agreeable room conditions in the restaurant, and at the same time maintain an acceptable noise level and compliance with the architectural features of the building.

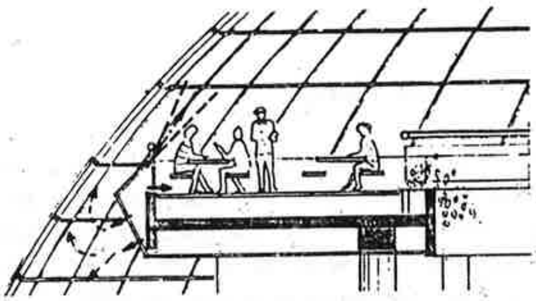

Fig. 2 The restaurant seating area on a revolving floor

In order to meet these demanding criteria, the displacement principle of introducing ventilation air was adopted for the vertical part of the wall. Furthermore, a row of individual single line diffusers was installed on the sill by the top of the wall. To enhance air distribution from the linear diffusers and to carry the ventilation air across the 5 m wide revolving floor, the carrying air jet method was adopted. The arrangement is demonstrated in figure 3. A total of 3.3 m^3/s, or two thirds of the air issuing from the wall, is introduced through the displacement panels. The remainder is directed through the linear diffusers and the carrying air jets. Substantial quantity of air from the fourth floor flows up through the space between the wall and the window induced by the air jets.

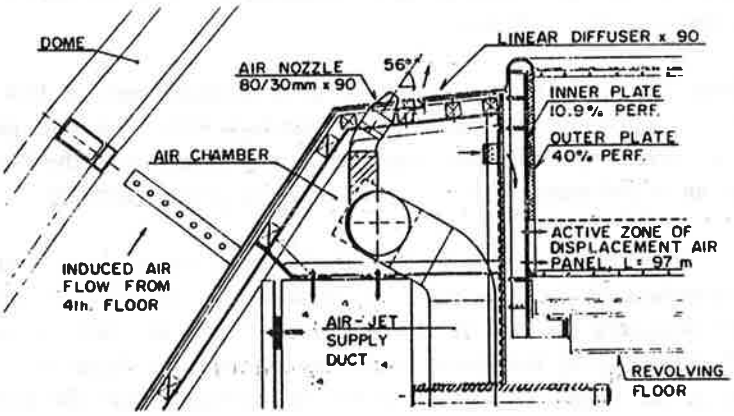

Fig. 3 Arrangement of air nozzles and air displacement panels

AIR DISPLACEMENT PANELS

The air displacement panels are a sandwich construction of two types of perforated plates, as indicated in figure 3. In order to obtain the pressure drop through the panels needed for even air distribution, the inner plate has a 10.9% perforation of 3 mm diameter holes. The flow velocity through the inner plate is 2.1 m/s at the maximum flow rate, i.e. 3.3 m3/s in cooling mode, and the associated pressure drop approximately 25 Pa. The outer plate has a 40% perforation and 4 mm diameter holes in a triangular pattern. The resulting average flow velocity through the outer plate is 0.6 m/s. The height of the air displacement panels is 150 mm and the overall length, which is the circumference of the surrounding wall, is about 97 m.

CARRYING AIR JETS

Air nozzles are placed at the outer side of the linear diffusers as seen in figure 3. The purpose is to induce air from the lower floor in addition to carrying the air issued from the linear diffusers.

Dimensonal analysis suggests that the width of a free air jet increases linearly with the axial distance x, and so the velocity on the axis is given by $v_x = \text{constant}/x$ for a circular jet. Experiment shows this rule to be closely followed. The angle of divergence is between 20° and 24° for a circular jet, reference [1], and about 5° greater for a jet issuing from a rectangular slit.

The flow pattern of a free air jet may be divided into three flow regimes, i.e. a core, transition zone and fully established turbulent flow, see figure 4.

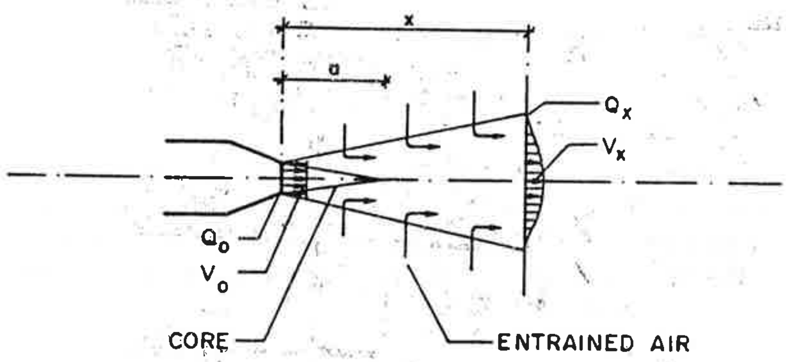

Fig. 4 Free air jet

In the core the velocity is constant and equal to that at the exit of the nozzle. Experiments show the core to have a conical form, and that the distance a between the nozzle exit plane and the apex of the cone is dependent upon the turbulence level. For laminar flow, $a=10d$, and for fully turbulent flow $a=3.3d$, where d=nozzle diameter, see references [2,3]. Reference [1] gives $a=4d$ for fully turbulent flow.

Downstream of the core there is a transition zone of length $8d$ where the velocity varies as, see reference [1]:

$$v_x=v_o\text{sqrt}(k'd_{vc}/x)$$

d_{vc} is the diameter of the jet at the vena contracta and k' is a constant.

At a greater distance from the nozzle exit, $25d$ to $100d$ [1], turbulent flow is fully established, and the velocity of the air along the nozzle axis varies hyperbolically with distance, see reference [3]:

$$v_x=v_o(a/x)$$

This may also be expressed as, reference [1]:

$$v_x=k'Q_o/x\text{sqrt}(C_dA_o)$$

$$=k'C_dA_ov_o/x\text{sqrt}(C_dA_o)$$

or $$=v_o(a/x) \qquad (1)$$

where $a=k'\text{sqrt}(C_dA_o)$

Thus, the constant k' may be defined as:

$$k'=a/\text{sqrt}(C_dA_o) \qquad (2)$$

When a jet encounters stationary fluid it sets some of this in motion, a process known as entrainment; Air from the surrounding atmosphere flows slowly in a radial direction towards the axis and is carried away in the direction of the jet, figure 4. The flow rate Q and also the jet diameter increase linearly with the distance x from the nozzle exit.

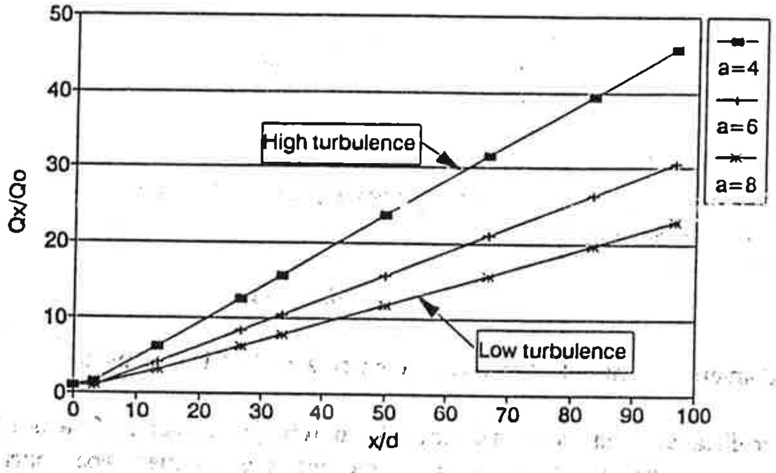

Fig. 5 Entrainment ratio of a free air jet

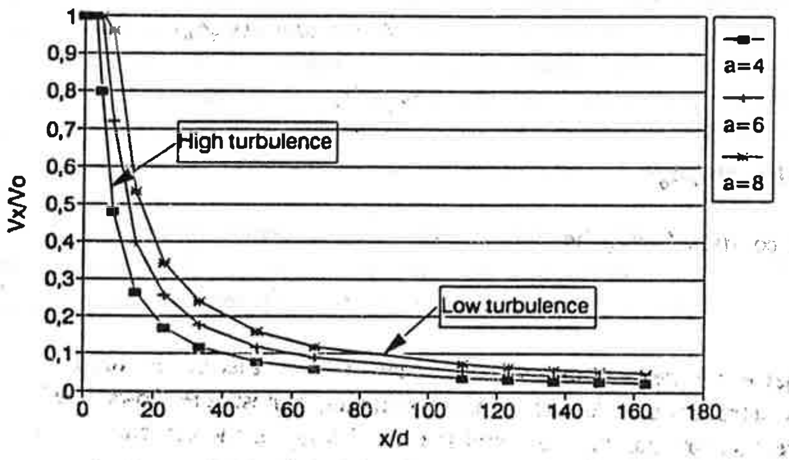

Fig. 6 Axial velocity of a free air jet

The entrainment ratio is expressed as [1]:

$$Q_x/Q_o = 2x/k'\text{sqrt}(A_o) \tag{3}$$

The throw is defined as, reference [1]:

$$x = k'Q/v_o\text{sqrt}(C_d A_o)$$

Maximum throw is often defined as the distance at which the centerline velocity has decreased to 0.2 m/s. Thus the throw L is:

$$L = 5k'Q/\text{sqrt}(C_d A_o) \tag{4}$$

The dimensions and flow rates of the nozzles used in the "Pearl" are the following:

$d = 30$ mm
$A_o = 707$ mm^2
$Q_o = 7$ l/s
$v_o = 10$ m/s

The air entrainment, or the mass of air put in motion by the action of the air jets, is given by equation (3). Depending on the turbulence level in the nozzle exit, the entrainment ratio at $x/d = 100$, or at 3 m distance from the nozzle exit, is 22 to 48, see figure 5, which corresponds to 150 to 300 l/s from each nozzle. If it is assumed that the induced air flow by each nozzle is 200 l/s at 3 m distance from the surrounding wall, the total entrained air mass at that distance is about 18 m^3/s. A considerable part of the entrained air comes from the fourth floor up through the space between the wall and the dome surface.

The throw, i.e. the distance at which the centerline velocity is reduced to 0.2 m/s is 6.2 m, if the air jet travels uninterrupted, see figure 6. The velocity drops rapidly off away from the centerline, and the resulting throw is correspondingly shorter.

CONCLUSION

The difficult problem of having to introducing large quantities of ventilation air close to the visitors of the restaurant was solved by adopting the displacement air principle and carrying air jets. This solution has proved to be very efficient during the different conditions occuring throughout the year, for cooling as well as heating operation.

REFERENCES

[1] **1989 ASHRAE Handbook, Fundamentals.**
American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

[2] **Fluid Mechanics: A Laboratory Course.** M. A. Plint and L. Böswirth, Charles Griffin & Co. Ltd., 1978

[3] Ricou, F. P. and Spalding, D. B. (1961), "Measurements of Entrainment by Axisymmetrical Turbulent Jets".
Jl Fluid Mech. Vol. 2, Pt. 1.