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MODEL EXPERIMENTS IN 1990 AND ON SITE VALIDATION IN 1992 OF THE AIR MOVEMENT IN THE DANISH PAVILION IN SEVILLA

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ABSTRACT

The purpose of this paper is to present the ventilation design concept, the model experiment results and the final measured values from the Danish Pavilion project. The reason for presenting these values is that the Danish Pavilion's indoor air climate was excellent and the architecture outstanding, despite the fact that the indoor pollution load was high (smoking, perfumes, tightly packed people) and the ventilation system was cheap and simple. It is suggested that the combination of higher air temperatures and higher air velocities, "summer breeze design", as used in the Danish Pavilion, may be applicable and cost effective in other building projects.

INTRODUCTION

The background for this presentation is the first author's practical experience in over 50 building projects and the second author's extensive experience in air movement modelling. The nature of a pavilion for a World Exposition allowed experiments, while the low budget required imagination. The resulting design concept and system were tested in model experiments which confirmed that the simple ventilation system gave results compatible with the concept. Results from Sevilla, both as measured and as positive response from the guests and owners, confirmed that the model experiments generally reflected the factual conditions (1).

PROJECT HISTORY

The Danish Pavilion concept was developed by KHR A/S Architects in 1989 and entered the design phase in January 1990. Bidding and negotiations took place from October 1990 and prefabrication began in January 1991. In August 1991 the complete prefabricated building was shipped from Denmark to Spain. Erection in Sevilla was complete in November 1991 and in March 1992 all services were functioning. On April 20, 1992, the World Exposition EXPO '92 opened and ran to October 12, 1992. The Danish Pavilion has been bought by Tamba State in Japan and dismantling of the pavilion was completed in December 1992. The Pavilion arrives in Japan on February 3, 1993, and is expected to be opened by the Japanese Emperor on May 9, 1993.

The project economy is mentioned briefly because the lack of funds stimulated the creative design process at the same time as it required the clients to accept the uncertainty involved in experimental design solutions. The initial target figure was 17 mill. DKK (~ 3 mill. USD) which was raised during the design phase to 24 mill. DKK. The lowest bid was 49 mill. DKK which after extensive re-selections and negotiations ended with the final account at 28 mill. DKK.

THE BUILDING AND THE VENTILATION SYSTEM

The building has two main elements: a steel framed "container" structure, facing west, with a floor area 45.0 m × 2.5 m, and a height of 24 m, and a glass fibre "sail" construction, facing east, which leans against the container structure. The large room thus formed between the "sails"and the "containers" is enclosed by glass walls to the north and south. This room was the exhibition room and was visited by over 800,000 people during EXPO '92. It was important that the indoor air quality was acceptable, preferably excellent, and that any technical equipment to provide this indoor air quality was in aesthetic harmony with the building, as well as being as cheap as possible. The room had a maximum capacity of 300 people and a volume of 9000 m^3 with an average height of 18 m.

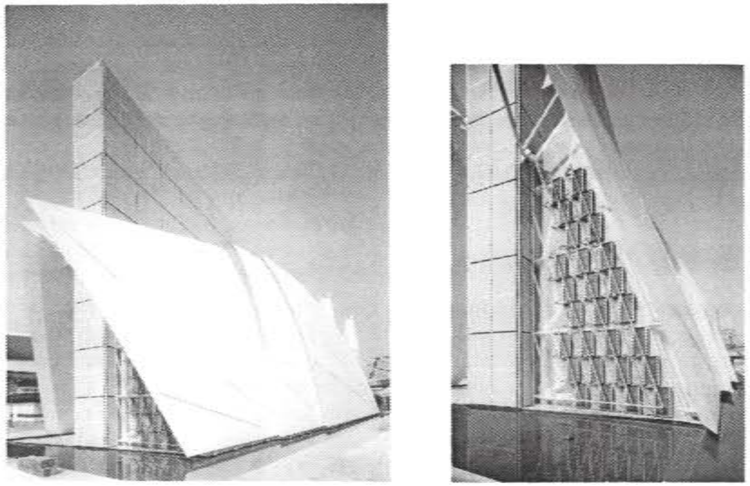

Fig. 1. a) The Danish Pavilion at the World Exposition EXPO '92 in Sevilla. b) Cooling elements in the south gable.

People in the exhibition room were their own main contaminants. With a floor loading of 1 person every 1,5 m^2, with a continuous show, and outdoor temperatures in Sevilla regularly reaching 40 °C, it was important for the comfort of the visitors, and the success of the exposition, that contaminant dilution was effective.

It was very quickly determined that a traditional air-conditioning system for this exhibition room could neither be accepted architecturally nor economically. Numerous alternatives and ideas were investigated, and the nature of the pavilion and the concept of a World Exposition encouraged the pursuit of experiments. It was decided to investigate the hypothesis presented by the first writer that "good indoor air is outdoor air", meaning that nature's air conditioning system is the best for the type of activity in the exhibition room, and that a light breeze on a warm summer day is something most

people enjoy. This concept was translated into a requirement for relatively high indoor air temperatures, 26 - 30 °C, and room air velocities up to 1 m/s instead of the normal limiting figure of 0,15 m/s.

The above concept reduced the requirements for cooling capacity and distribution ductwork, satisfying both the client's budget and the architect. The selected design was based simply on installing exposed cooling elements in the south gable of the room and an extract fan in the top north end of the room. Air is drawn through the cooling elements, where it cools and falls to the floor (2).

AIR DISTRIBUTION IN RESTAURANT AND EXHIBITION SECTION

The occupied zone design load of the restaurant and exhibition hall is 48 kW corresponding to 300 persons in the pavilion. The equipment for slide and video will generate another 130 kW which is expected to move upward in convective flows giving a high temperature in the upper part of the pavilion. This part of the heat load will be extracted with the upper ventilator at a high temperature effectiveness.

The heat load transmission from outside will be small because two sides of the pavilion are formed as an air conditioned building and a water cooled fibre glass sail. The north wall is a glass window and the south wall - where solar radiation is present - is the inlet wall with cooling devices.

Inlet air temperature of 26 °C was considered the low limit, and an upper limit of 30 °C was chosen, relative to an outdoor temperature of 38 °C. This required a maximum 4°C horizontal temperature gradient in the room, without "hot spots" indicating stagnation. The corresponding minimum ventilation air volume is thus 10 m^3/s. At the same time it was important that room air velocities in the cooler, south end of the exhibition room were not excessive and that a local limit of 1 m/s was selected.

All these parameters were tested in August 1990 in a climate laboratory by modelling (3), and were confirmed by site measurements in May 1992.

MODEL EXPERIMENTS

The model experiments were made in a model with the scale 1/10. Experience with measurements on flow from wall mounted diffusers for displacement ventilation indicates that it is possible to ignore the level of the Reynolds number at the given dimensions as discussed in (4), which will enable reasonable temperature differences in the model experiments.

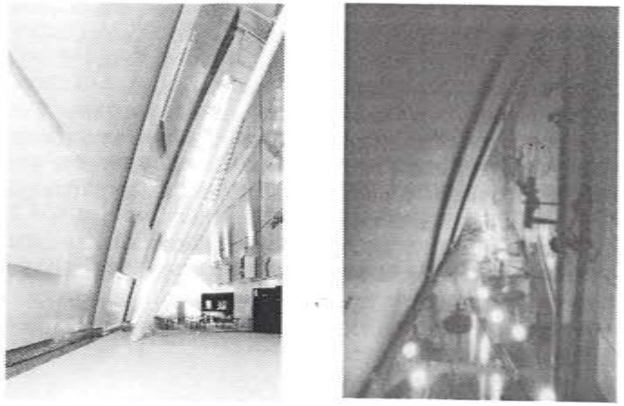

Fig. **2.** Restaurant and south wall with the cooling device in full scale and in model.

Figure 2 shows the model and the space in full scale. Sixteen different experiments were made in the model and two of the more essential ones will be discussed in details in the following

Table **1.** Conditions and results for two model experiments.

	h (m)	ΔT_o (K)	u_f (m/s)	Ar	$\frac{u_m}{u_f}$
Test A	1.2	5.6	0.26	3.35	1.1
Test B	1.2	7.5	0.175	9.84	1.8

The Archimedes number in the experiments is based on the height h of the inlet device as the length scale and the face velocity u_f as reference velocity, where face velocity is the supply flow divided by a reference area (~ 60% of the end wall area).

Figure 3 shows the normalized velocity distribution in the room as a function of the Archimedes number. It is quite obvious that the flow is a stratified flow with the highest velocity in the occupied zone. Smoke measurements show that the cold air from the cooling device accelerates down into the occupied zone, due to gravity, and moves horizontally along the floor in the restaurant and exhibition section.

Measurements show that the velocity has a fairly constant level in the occupied zone, even far downstream from the wall with the cooling device as shown on figure 3. The flow is plane and it is a general experience that the velocity in plane stratified flow is constant and independent of distance from the inlet device.

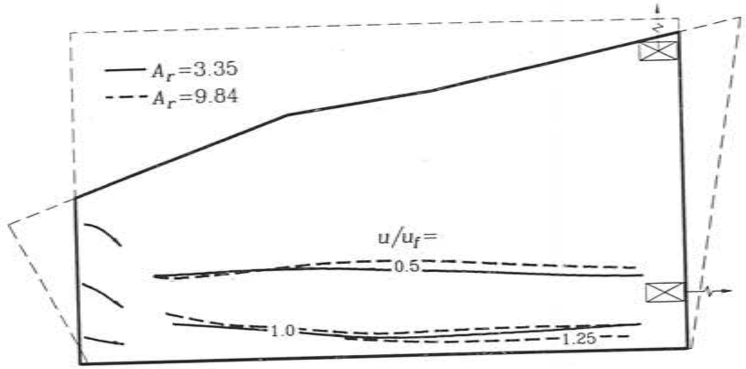

Fig. **3.** Normalized velocity distribution versus Archimedes' number.

Table 1 shows that the normalized maximum velocity in the occupied zone u_m/u_f has the level of 1.1 in test A and the level of 1.8 in test B. The higher velocity level in test B is also obvious on figure 3.

The influence from the location of the return opening was tested by using the lower opening alone, the upper opening alone and a combination of both openings with 50% flow in each. It was not possible to measure any effect on the velocity level in the model. Experiments with a variable temperature at the surface of the supply device, with the highest temperature in the upper part of the device, did not show any pronounced influence on the velocity level.

The velocity in the stratified flow is generated by a downward acceleration due to gravity effect on the cold air from the supply device. This gravity effect can be counteracted by a number of nozzles at the inlet device which supply upward directed jets with a high momentum flow. Measurements at an arrangement of this type show that it is possible to make a considerable reduction in the velocity level in the restaurant section, but the exhibition section will retain the velocity level obtained without the high momentum jets.

TRANSFORMATION OF MODEL EXPERIMENT TO FULL SCALE

The volume flow rate from the cooling device in the south wall is designed to 10 m^3/s. This is equivalent to a face velocity u_f of 0.35 m/s. The Archimedes number in test A corresponds to a temperature difference between the return and the supply device of 1 K, corresponding to a heat load of 12 kW in the restaurant and exhibition hall. This is a rather restricted head load and the model experiments show that the maximum velocity in the occupied zone will be 0.4 m/s in full scale. A heavier load of 36 kW - corresponding to test B - will give up to 0.6 m/s in the occupied zone.

Economical considerations and a later design of light blinds made it impossible to use high momentum jets in the final solution. There were also some changes in the design of the cooling device in the wall. This will probably have the effect that the entrainment into the cold flow close to the wall will be higher in the full-scale situation compared with the entrainment in the model experiments, which means that the model experiments will make a slight overestimate of the velocity level.

MEASURED VALUES ON SITE IN MAY 1992

On site measurements show air velocities at the level of 0.8 m/s corresponding to the velocity level obtained by the model experiments, although they show a quicker reduction than expected. The measurements could only take place in the early morning of May 6th, 1992, when the outdoor temperature was 19.7 °C. An artificial heat load was induced by reducing the inlet air temperature to 12.1 °C, corresponding to an air load of 52 kW. Show projectors and lighting were at full power whereas occupant loading was light, approximately 20 people. Discharge air temperature was 27,5 °C, indicating the expected strong vertical stratification corresponding to a high ventilation effectiveness.

Table 2. On site measurements 1 m over floor level. Maximum velocity and mean temperature measured across the room versus distance from inlet.

Distance	Temperature, °C
2 m	12.7
16 m	14.1
24 m	14.6
32 m	14.9
40 m	14.7

Distance	Velocity, m/s
2 m	0.6
3 m	0.6
5 m	0.8
8 m	0.5
12 m	0.1

The conclusions from on site measurements are: (a) Uniform temperature distribution in the occupied zone with a small horizontal temperature gradient. (b) Strong vertical stratification ensuring separation between occupied zone loads and other room loads. (c) Air velocities equal to or lower than those predicted by model experiments.

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