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NATURAL CONVECTION AIRFLOW AND HEAT TRANSPORT IN BUILDINGS: EXPERIMENTAL RESULTS

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ABSTRACT

Observations of natural convection airflow in passive solar buildings are described. Particular results are given for two buildings supplementing other data already published. A number of generalizations based on the monitoring of the 15 buildings are presented. It is concluded that energy can be reasonably well distributed throughout a building by natural convection provided suitable openings are present and that the direction of heat transport is either horizontally across or upward.

1. INTRODUCTION

A series of experiments was initiated in 1981 to determine the nature of natural convection airflow, heat distribution, and stratification in passive solar buildings. This work grew out of a realization that natural convection plays a significant role in the distribution of heat from warmer to cooler rooms of a building. Some of our earlier results have been reported at the 8th and 9th Passive Conferences (1,2). A more comprehensive report of results up through October 1984 is given in Ref. 3. The purpose of this paper is to describe a few of the most recent results and to present unifying generalizations that we have distilled from our observations. We have now taken data in 15 buildings including two atria in commercial buildings. Flow visualization techniques using both smoke and neutral-density soap bubbles have proved to be quite helpful, although the most useful data are air velocity and temperature measurements. These can be integrated to obtain airflow and heatflow rates. We have learned that the seemingly complex character of natural airflow inside the complicated geometries of actual buildings obeys some fairly simple laws leading to optimism that the processes can be quantified so that the principles can be incorporated into design practice. The importance of aperture restrictions in determining airflow rates between rooms has been established and simple equations have been developed for obtaining reasonable estimates in simple and more complicated geometries. An interdependence of stratification and room-to-room energy transport has been observed. Work has begun on a mathematical model that adequately describes the physics and yet is simple enough for analyzing actual buildings (4,5).

2. AIRFLOW IN A SHORT HALLWAY

A 4 ft. hallway connects the center upstairs bedroom to a balcony which extends into the two-story-high sunspace of the Balcomb solar house (6). Both smoke traces and neutrally-buoyant, helium-filled soap bubbles indicate that the air passing along this hallway through the doorways at each end does not flow horizontally. The warm air streamlines tend to rise about 1 ft. as they pass down the hallway from the balcony toward the cooler bedroom and the returning cool air streamlines tend to fall the same distance so that there exists a sloping, zero-velocity plane in the hallway. Once through the bedroom doorway the warm air rises quickly to the ceiling.

Velocity profiles measured in each of the doorways are shown in Fig. 1 indicating a significant change in profile shape from one end of the hall to the other end. Two measurements were made at each height and the results averaged. Maximum and minimum values of the anemometer needle fluctuations were noted and used to determine maximum and minimum flow integrals in each direction. Since the average of these four flow rates fall within the range of each pair of measurements it was assumed that the flow inward equals the flow outward and is the same in each doorway.

Note that the zero velocity point is about 10 in. higher for aperture 1, the doorway closest to the bedroom, than for aperture 2, in general agreement with the flow-visualization results described

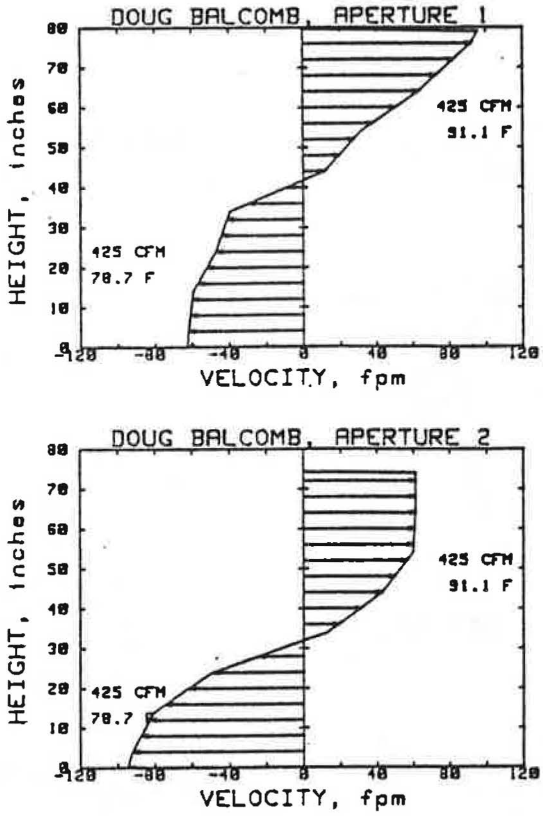

Fig. 1. Velocity profiles for two doorways in series at each end of a short hallway. Aperture 1 is closest to the cool room and aperture 2 is closest to the warm room.

above. Also note that neither profile is symmetric; there is a tendency for the highest velocities to occur at the top of aperture 1 and at the bottom of aperture 2; also, there is a tendency for the velocities near the bottom of aperture 1 and near the top of aperture 2 to level off.

The temperature difference between the sunspace and the bedroom, measured at the same elevation, was 15.5°F at the time these measurements were taken, at about 2:00 p.m. on a moderately sunny day. The energy transport is 4380 Btu/h. The doorway dimensions are 79.6 by 30.5 in. (aperture 1) and 74.3 by 30.3 in. (aperture 2).

3. ATTACHED SUNSPACE

A 210 sq. ft. sunspace was attached as a retrofit to an existing house in Los Alamos. The south glazing area 144 sq. ft. deployed as follows: 26 sq. ft. vertical, 42 sq. ft. curved, and 76 sq. ft. at a 15° end of March but due to the sloping glazing there was still sufficient solar gain to drive strong convective flows into the adjacent bedroom of the house. Shading of the overhead glass and ventilation, which would normally have been used to prevent overheating in this season, were not employed during our experiments.

The data presented here, which represent only a small fraction of all of the data taken, were obtained during two consecutive completely sunny days. The door, which connects the sunspace to the house, was closed on day 91 and open on day 92. Although solar conditions were almost identical on the two days, the average outside temperature was 36°F on day 91 and 46°F on day 92. Despite this difference the sunspace was markedly hotter with the door closed than with the door open, as shown on Fig. 2. Just the opposite is true of the bedroom, which has no direct solar gains.

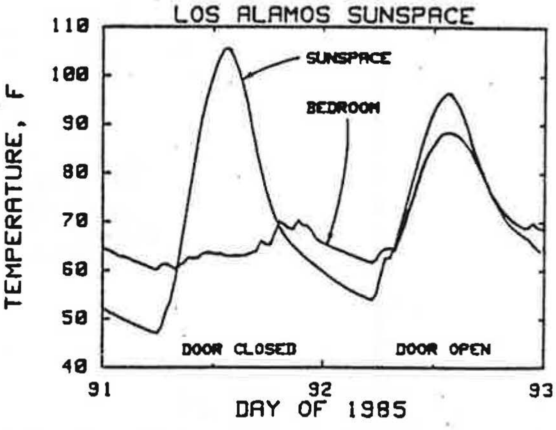

Fig. 2. Air temperatures in the sunspace and adjacent bedroom, measured at 60" above the sunspace floor, on two subsequent days. The connecting door was closed on the first day and open on the second.

Stratification in the sunspace is shown in Fig. 3. Note that stratification is much more pronounced when the door is open and there is strong convective exchange to the adjacent bedroom than when the door is closed. There is virtually no stratification at night. The sunspace has a massive floor (brick on concrete slab) and a massive north wall (grouted concrete block); however the other walls and the bedroom are of lightweight construction. During this season most of the direct sunlight hits the floor and only the lower 12 in. of the north wall is directly sunlit. Floor temperatures and wall temperatures are shown in Figs. 4 and 5. Note that the sunlit areas are indeed warmer than areas persist into the evening as energy redistributes within the enclosure. Also note that there is little difference between the wall temperatures on the two days.

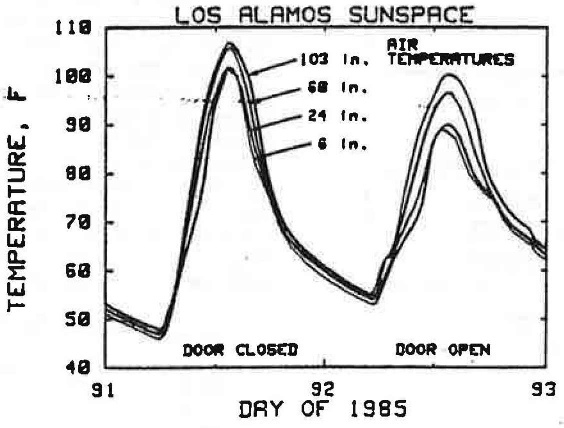

Fig. 3. Sunspace air temperature vertical profile showing much greater stratification when there is convective exchange through an open doorway.

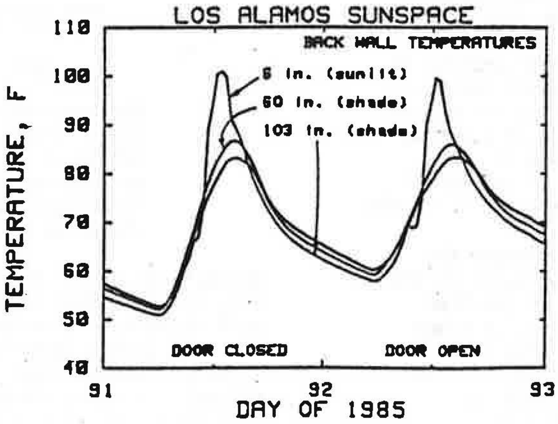

Fig. 4. Surface temperatures measured on the north wall of the sunspace at different heights. The wall is 8 in. grouted concrete block, insulated on the outside.

4. GENERALIZATIONS BASED ON THE DATA

We have taken a great deal of data, either in raw form or slightly processed. Several clear patterns that emerge from these observations are discussed below.

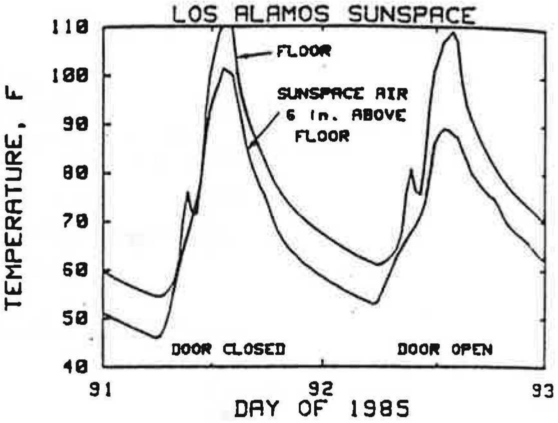

Fig. 5. Floor surface temperature measured near the center of the sunspace. The floor consists of brick pavers laid on a 4 in. concrete slab. Note that the floor is always warmer than the air above.

A. Energy Distribution by Natural Convection

Energy can be reasonably well distributed throughout a building by natural convection, provided suitable openings are present. Although distribution to upper rooms is favored, this is not unreasonable from a comfort standpoint because these rooms usually have a greater heat loss due to the roof. Even north remote rooms at the lower level will receive significant heat by natural convection, although the temperature will generally be somewhat lower than for upper rooms. The system tends to be strongly self balancing because heat convection from a warm area to a cold area increases as the 1.5 power of the room-to-room air temperature difference.

B. General Airflow Profiles

The general profile of airflow velocities through most apertures is quite well characterized by the simple theoretical parabolic (square-root) profile based on the Bernoulli equation (2). We usually note the following small variations from this profile.

a. The velocity near the floor is greater than for the parabolic curve, forming a tail on the bottom of the profile that is nearly linear. This is probably due to pooling of cold air near the floor of the cool room that rushes through the doorway.

b. The velocity gradient near the center of the doorway is less than the infinite gradient that is predicted by the simple theory. This straightening of the profile near the zero velocity crossover point may be due to viscous or eddy-induced drag of the air, an effect that is nearly negligible along the rest of the profile.

c. The observed velocity is not steady but fluctuates slowly. The relative fluctuation is greatest at low velocities and least at high velocities where the flow tends to be quite steady.

Other departures from the theoretical profile are most noticeable when there is little flow due to a low driving delta T or when there is a major constriction near the door, such as a wall or piece of furniture.

The flow velocity tends to be reasonably uniform across the doorway at a constant height. The major exception is when the flow is turning into or out of a hallway, in which case the velocity will be greater on the inside of the turn as the air tries to cut across by the shortest path.

There is also general agreement between the simple theory and flow profiles observed in multiple aperture geometries. A particularly clean case was studied where two doorways connecting two spaces are offset in height. The profiles match the theoretical result reasonably well and the reasons for the minor variations from theoretical are understood. In most cases the major profiles are all quite understandable, however there are a few cases where deviations from the normal profile shapes are pronounced and not well understood.

C. Variation of Velocity with Delta T

The simple theory also predicts that the velocity at a particular height in an aperture will be proportional to the square root of the room-to-room temperature difference. This is well born out in the experimental data. The scatter of data points (usually 1/2 hour averages of 300 samples) show no more that about 10% random variation from this functional dependence and no systematic variation in most cases. The slope of the lines is quite close to the theoretical slope.

D. Doorway Temperature Profiles

The ratio, (door-top-to-door-bottom delta T) / (room-to-room delta T), is usually bracketed within the range 0.8 to 1.3 during periods of strong convection. This empirical result seems to be part of the nature of the stratified flow. Because the airflow rate can usually be predicted within ± 15%, this means the instantaneous energy transport can be predicted to within ± 35%. The estimate of the energy transport integrated over a day may be somewhat closer. Stratification in the doorway tends to be much steeper than in the adjacent rooms. This is noted also in the profiles measured in similitude experiments. These profiles suggest that the streamlines shift levels approaching an aperture, downward on the cool room side and upward on the warm room side.

E. Glass Temperatures

Observed sunspace glass temperature swings are huge, usually about 20°F greater than room air swings. The glass is about 10°F warmer than the air when in the direct sun and 10°F cooler at night. Glass surfaces are usually dominant heat transfer areas in a sunspace and have a very pronounced effect on comfort.

F. Stratification

The most general statement that can be made is that stratification (0.5 to 1.2°F/ft.) is observed in every case where there is significant zone-to-zone convection through apertures. The evidence strongly suggests that convective exchange and stratification are strongly linked, although the physical reasons are not yet completely clear. Stratification is much stronger when two spaces are convectively linked by air flow through a common aperture than when convection is blocked.

G. Hybrid Systems

In the course of studying natural airflow, we have also monitored the performance of a few fan-forced hybrid designs. The performance of these has been disappointing, especially compared with the good performance of natural convection. In one case, the fan proved counterproductive in every aspect. We believe that the problem usually lies in details of the design. Like other active solar systems, fan-forced systems must be carefully engineered and properly installed if they are to work correctly. A major advantage of fan-forced flow is the ability to move heat downward and store it, for example, to move heat from the top of an atrium into the floor structure of a remote room. Natural convection can only move heat downward to a limited extent and would generally not be effective for under-floor storage. The principal advantage of the hybrid systems we have observed lies in improved thermal comfort rather than in energy savings.

H. Vent Pairs vs Doorways

Some commonly held beliefs of passive solar design have been brought into question by our findings. An example is the notion that pairs of high and low vents are a preferable geometry for natural energy exchange. In one case studied, the addition of a high vent did not enhance heat transport. We find that ordinary doorways can usually serve quite adequately and have many other advantages.

I. Level Changes

The effect of a level change, such as a step or series of steps between spaces, has been investigated. The data are not conclusive, but do suggest strongly that level changes can be quite effective. Further work is warranted to investigate this issue.

J. Thermal Comfort

Our investigations have been broadened to include the issue of thermal comfort in passive solar spaces. Air motion by natural convection can serve not only to distribute heat in a building, but can markedly improve comfort in overheated conditions that may tend to exist under peak solar gain. In one case studied, increasing aperture size actually decreased thermal transport but did increase comfort due to increased air velocities.

K. Ducts for Return Air

In two cases, passive return air ducts were installed. Although these did aid in providing return airflow, it is questionable whether the added performance warrants their expense. It is probable that the same performance could have been achieved at lower cost and greater convenience using normal architectural elements such as stairways, hallways, door, windows, and rooms that can serve multiple purposes.

5. ACKNOWLEDGEMENT

Mark White assisted in taking some of the data which are presented. Prof. David Otis made valuable suggestions.

6. REFERENCES

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