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HEAT DISTRIBUTION BY NATURAL CONVECTION

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ABSTRACT

Natural convection can provide adequate heat distribution in many situations that arise in buildings. This is appropriate, for example, in passive solar buildings where some rooms tend to be more strongly solar heated than others. Natural convection can also be used to reduce the number of auxiliary heating units required in a building. Natural airflow and heat transport through doorways and other internal building apertures is predictable and can be accounted for in the design. The nature of natural convection is described, and a design chart is presented appropriate to a simple, single-doorway situation. Experimental results are summarized based on the monitoring of 15 passive solar buildings which employ a wide variety of geometrical configurations including natural convective loops.

INTRODUCTION

Natural convection plays the major role for distribution of heat in many passive solar buildings, especially those that employ sunspaces or atria as solar heat collection elements. Another example is a single remote room on the north side of the building heated by natural convection through a doorway. This convective exchange usually involves normal architectural elements such as doorways, hallways, rooms, and stairways. Los Alamos has measured data in 15 different building geometries to thoroughly understand this complex process. Detailed measurements of air velocities and temperatures have been used to determine airflow and energy transfer rates. Similitude experiments have been performed in the laboratory using Freon gas to simulate air in approximately 1/5 scale. The results have implications not only for passive solar heating, but for natural cooling techniques. In many situations natural convection is an adequate mechanism for heat distribution, and one does not need to rely on complex and expensive mechanical equipment and controls which may not work as well or as reliably.

NATURE OF NATURAL CONVECTION THROUGH APERTURES

Two-way airflow is normally observed in a doorway separating two rooms at different air temperatures. Airflow rate depends on the aperture geometry and on the room-to-room temperature difference, ΔT, measured at the same elevation in each room. Typical results are shown in Fig. 1 for the case of a 0.875 by 1.98 m doorway separating a sunspace from the adjacent house. The value of ΔT in this case is 7.5°C, taken sunny, mid-day conditions. The flow rate can be determined by integration of the velocity profile. Within the range of variations observed a mass-flow balance can be forced and the best estimate of flow rate in each direction is 14.5 m^3/min.

Brown and Solvasen [1] derived a simple analytical expression for the velocity profile base on the Bernoulli equation. The result is a velocity which varies as the square root of the vertical distance from the aperture mid-plane and as the square root of ΔT. The experimentally observed profile shape is reasonably well represented by this theory. The flow rate determined by integrating the theoretical profile is given by:

$$V = 2.21\ w \sqrt{h^3\ \Delta T} \quad ,$$

where V = volumetric flow in each direction, m^3/min,
w = door width, m,
h = door height, m, and
ΔT = room-to-room temperature difference, °C.

This equation predicts a volumetric flow rate of 14.75 m^3/min for the situation depicted in Fig. 1, in close agreement with the observed flow rate. We have observed similar close agreement in many other cases.

Energy transport is determined by the airflow rate and the difference between the mixed-mean temperatures of the upper airstream and the lower airstream. If the airflow rate is V and the mixed-mean temperature difference between the upper and lower airstreams is ΔT_d, the energy transport rate, Q, in watts, is

$$Q = (20)(V)(\Delta T_d) \quad ,$$

The number 20 in this equation is the volumetric heat capacity of air (W-min/m^3°C) at sea level. At higher elevations, the value will be less in direct proportion to air density. If we combine these two equations, the result is

$$Q = 44.1\ w \sqrt{(h\ \Delta T)^3}(\Delta Td/\Delta T) \quad .$$

Temperature profiles taken at the same time as the velocity profile of Fig. 1 are shown in Fig. 2. Energy flow can be determined by integrating the product of temperature and velocity. The result is an energy transport rate of 2.17 kW. The observed value of $\Delta Td/\Delta T$ is 1.29 at this time, and the air density is 0.77 of sea level air density. Using these values the energy flow predicted by the energy equation is 2.19 kW, in excellent agreement with the observed value.

The profile of energy flow through the day is shown in Fig. 3. The integral under the curve is 14.3 kWh convected through the doorway to the house.

A single remote room in a building can often be adequately heated just by natural convection from an adjacent heated space. Based on the equations given earlier, we can relate the temperature difference from room to room, the room heat loss, and the aperture geometry. Here we assume that $\Delta Td = \Delta T$ which is reasonable if ΔT is small. If the temperature variations in the rooms are not greater than about 4°C, the equation has been shown to apply to average conditions with reasonable accuracy. The result is the design chart shown in Fig. 4.

NATURAL CONVECTIVE LOOPS

A convective loop, shown in Fig. 5, is between a two-story-high sunspace and the attached two-story house. We have measured several of these convective loop situations and found them to be very effective. Energy transport rates of 0.7 to 6.0 kW have been observed for room-to-room temperature differences ranging from 2°C to 5°C. Furthermore, good distribution of heat throughout the various rooms of the building is usually achieved, even to north rooms on the lower level.

A key advantage of the sunspace geometry, either single level or two story, is the separation of the building into two thermal zones. There will be large temperature swings in the sunspace and small swings in the living areas. A very effective thermal diode effect can be achieved by closing doors between the zones at night.

GENERALIZATIONS BASED ON THE EXPERIMENTAL RESULTS

We have found that the observed natural convection is predictable using relatively simple models, generally consistent with the equations presented earlier. In the future we plan to distill the results into several simple design charts, similar to Fig. 4, and also a set of design guidelines. A comprehensive description of interim results has been written by the author and will be published as a Los Alamos report. A few general observations are given below.

Variation of Velocity with $\sqrt{\Delta T}$

The simple theory, which predicts that velocity at a point in a doorway will vary as $\sqrt{\Delta T}$, is well borne out by the experimental results. Plots of velocity measurements versus $\sqrt{\Delta T}$ were made for several buildings using 1/2 hour averages of 300 data samples. The data were taken over several days and represent a wide range of ΔT conditions. The results generally show a good straight line with an apparently random scatter of no more than 10%. The slope of the lines is close to the theoretical value.

Stratification

The most general statement that can be made is that stratification (0.9 to 2.2 °C/m) 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.

Doorway Temperature Profiles

The ratio $\Delta T_d/\Delta T$, which appears in the doorway energy transport equation, is usually bracketed within the range 0.8 to 1.6 during periods of strong convection and tends to increase during the day. This empirical result seems to be part of the nature of the stratified flow. Stratification in the doorway is always steeper than in the adjacent rooms. These profiles suggest that the streamlines shift levels approaching an aperture, downward on the cool room side, and upward on the warm room side.

Glass Temperatures

Observed sunspace glass temperature swings are huge. The glass is usually warmer than the room air by about 6°C when the glass is in the direct sun and 5°C cooler at night. Glass surfaces are usually the dominant heat transfer areas in a sunspace and have a very pronounced effect on comfort.

Hybrid Systems

In the course of studying natural airflow, we have also monitored the performance of 4 fan-forced hybrid designs. The performance of these has been disappointing, expecially compared with the good performance of natural convection. In one case the fan proved counterproductive in every aspect. We observe 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 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.

Energy Transport by Natural Convection

Large energy transport rates are observed with modest values of ΔT. Table 1 summarizes the results from 10 of the monitored sunspace buildings.

TABLE 1 Summary of Convection Data Determined from Doorway Scans

Sunspace Height	Sunspace Glazed Area	Sunspace-to-House			
No. of Stories	m^2	Connecting Doorway Area m^2	Typical ΔT °C	Total Airflow m^3/min	Energy Transport by Convection W
2	37.2	7.4	3.3	47.4	5180
1	16.7	2.9	1.7	18.6	710
2	38.1	10.6	2.8	63.1	4540
2	52.9	4.5	5.5	47.0	6180
1.5	28.8	5.9	1.9	29.5	1460
2	19.5	7.6	2.2	33.5	1430
1	14.8	8.5	1.8	25.8	1211
1	20.2	1.7	7.5	14.4	2170
2	8.9	2.0	2.2	13.3	630
1.5	21.4	4.4	1.9	15.1	760

REFERENCE

1. W. B. Brown and K. R. Solvason, "Natural Convection Through Rectangular Openings in Partitions, Part I; Vertical Partitions," Int. V. Heat and Mass Transfer 5, pp. 859-868 (1962).

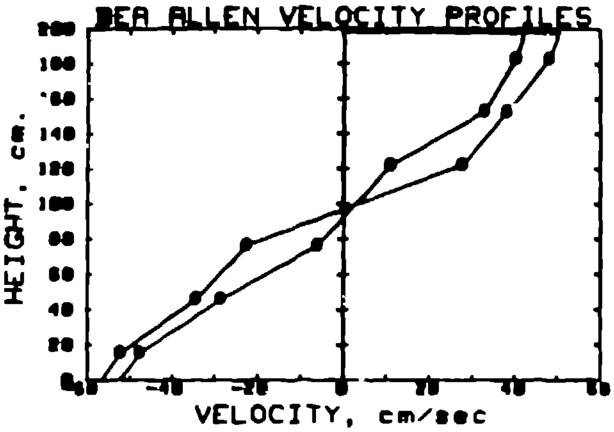

Fig. 1. Doorway velocity profiles measured at 13:20 on March 21, 1984. Maxima and minima of anemometer needle swings are observed and plotted. Each point is the average of two readings at different horizontal locations (1/4 and 3/4 points).

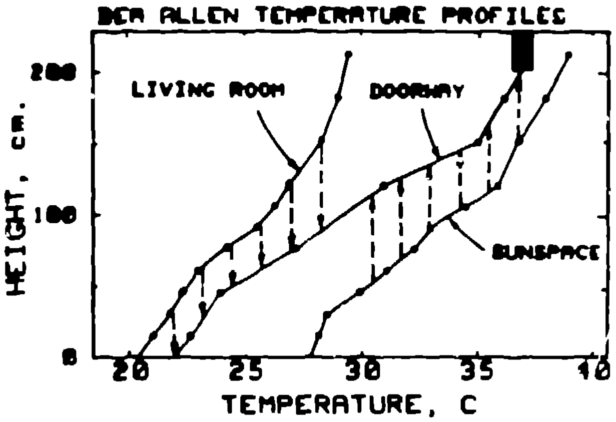

Fig. 2. Temperature profiles at 13:20 on March 21, measured in each room and in the doorway. Dotted arrows show the vertical displacements implied if streamlines are isotherms.

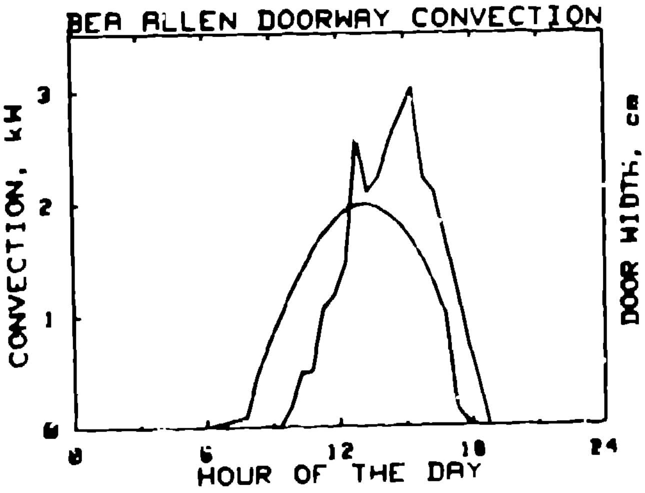

Fig. 3. Energy convected through doorway on March 20, 1984.

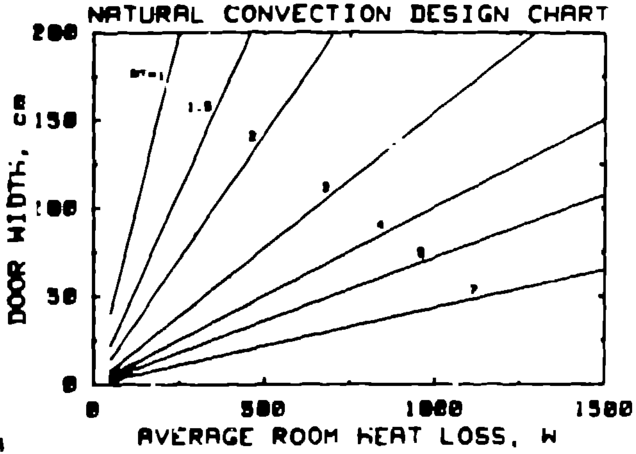

Fig. 4. Design chart for doorway width needed to heat a remote room by natural convection. The assumed door height is 2 m.

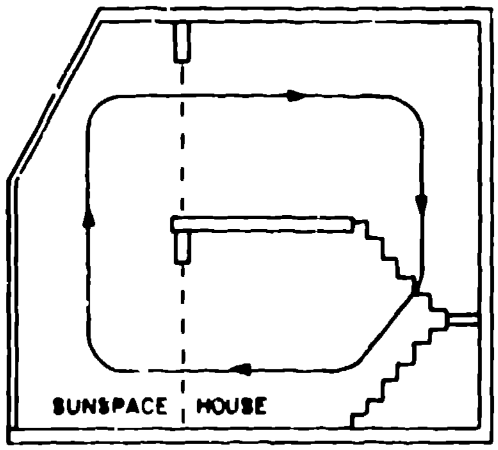

Fig. 5. Typical natural convective loop in a two-story house with a sunspace.