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NATURAL AIR MOTION IN PASSIVE BUILDINGS*

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SUMMARY

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. Natural convective loops that can occur in buildings are described and a few experimental results are presented. Observations of stratification are discussed, similitude experiments are described, and the beginnings of a complete-system mathematical model are presented.

INTRODUCTION

Natural convection plays the major role for distribution of heat in many passive solar buildings, especially those that employ sunspaces or atria as a solar heat collection element. Another example is a single remote room on the north side of the building. This convective exchange usually involves normal architectural elements such as doorways, hallways, rooms, and stairways.

Los Alamos has measured data in 15 actual building geometries to thoroughly understand this complex process. Detailed measurements of air velocity and temperature have been used to determine airflow rates and energy transfer rates. We have found that large natural convective exchanges occur with modest temperature differences and that one often finds a convective loop around the passages of a two-story geometry. We find that building geometry and aperture sizes have a major influence on both energy exchange rates and thermal comfort.

Simple relationships have been developed to predict energy exchange rates in particular situations, and these have been confirmed based on experimental observations. These relationships can then be used to develop design charts and graphs suitable for use in the layout of buildings. The results have implications not only to passive solar heating, but to 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 of questionable reliability.

THE NATURE OF CONVECTIVE EXCHANGE THROUGH APERTURES

Buoyancy-Driven Flow

If two adjacent spaces connected by a doorway through the common wall are at different temperatures, a natural convective exchange of air will occur through the doorway. Warm air will flow through the top of the doorway into the cooler room and cool air will return to the warmer room through the bottom of the doorway. The net effect is to transport heat from the warmer room to the cooler room, tending to decrease the temperature difference.

A typical air velocity profile observed in a doorway is shown in Fig. 1. The two counter-current air streams through the doorway are well behaved and do not mix appreciably. The flow velocity approaches zero at the door midpoint and increases as the distance from the door midpoint increases, reaching a maximum in one direction at the door

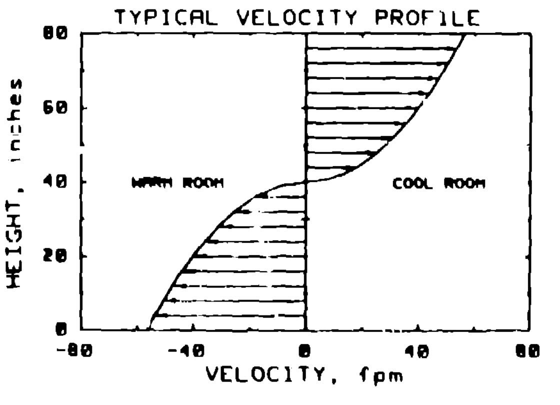

Fig. 1. Natural airflow velocities in a typical doorway with a 6°F temperature difference between rooms.

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*Work performed under the auspices of the US Department of Energy, Office of Solar Heat Technologies.

top and in the other direction at the door bottom. The velocity is proportional to the square root of the distance from the door midpoint and to the square root of the temperature difference between rooms. If the rooms are reasonably airtight, the top and bottom halves of the curve are symmetric and the airflow in each direction will be equal. Streamlines tend to be nearly horizontal in the doorway, and the boundary layers near the doorway edges are quite thin.

The airflow is buoyancy driven. This is because the air in the warm room is lighter than the air in the cool room and, thus, will tend to rise, while the air in the cool room falls. If the partition between the rooms were removed, creating one large room, the airflow would take on a simple circular pattern. However, the presence of a partition with an opening that is much smaller in area than the partition creates a major flow impedance between the rooms, and the opening becomes the governing element that controls the rate of energy transport.

An Example

Natural convection energy transport rates can be significant, as an example will show. Suppose that two rooms are separated by a partition that is 10 ft high and 20 ft wide, and the aperture is a normal 6-ft 8-in. door 3 ft wide. The partition area is 200 ft^2, and the door area is 20 ft^2. If the temperature difference between rooms is 6°F, the following will result (at sea level):

Airflow = 380 cfm, and
Energy transport = 2440 Btu/h.

Compare this to conduction through the wall. Suppose that the U-value from room-to-room is 0.4 Btu/ft^2 h °F, typical of an uninsulated stud-frame wall. The conduction heat transfer is 0.4 x 6 x 180 = 432 Btu/h. This is less than 1/5 the convective transfer rate. The heat transfer rate, per unit area, is 51 times greater for the opening than for the partition.

Airflow

Airflow rate depends on the geometry of the aperture and on the room-to-room temperature difference, ΔT, measured at the same elevation in each room. The following simple equation can be used to estimate the airflow for a simple rectangular aperture:

$$V = 2.98\, w\sqrt{h^3\, \Delta T}\ , \qquad (1)$$

where V = volumetric flow in each direction, cfm,
w = door width, ft,
h = door height, ft, and
ΔT = room-to-room temperature difference, °F.

This equation is derived theoretically and is well collaborated by experimental observation. The airflow does not depend on air density (which varies some with elevation) nor does it depend appreciably on temperature stratification that may be present in the rooms.

Energy Transport

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 cfm and the mixed-mean temperature difference between the upper and lower airstreams is ΔT_d °F, the energy transport, Q, is simply,

$$Q = (1.08)(V)(\Delta T_d),\ \text{Btu/h}. \qquad (2)$$

The number 1.08 in this equation is the heat capacity of air (Btu/°F ft^3) at sea level. At higher elevations, the value will be less in direct proportion to air density. ΔT_d, the temperature difference between the upper and lower air streams, is usually close to ΔT, the room-to-room temperature difference. If these two are equal, then

$$Q = 3.2\, w\sqrt{(h\, \Delta T)^3}\ . \qquad (3)$$

Design Chart

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. The result is a design chart as shown in Fig. 2.

As an example of the use of this chart, suppose a remote room in a building has a design heat loss of 1200 Btu/h and that, under these conditions, we are willing to allow an average room temperature 4°F below the temperature in the rest of the building. Then, from the chart, we see that a door width of 32 inches is needed to provide sufficient heat transfer by natural convection through a standard 6 ft 8 in. door opening.

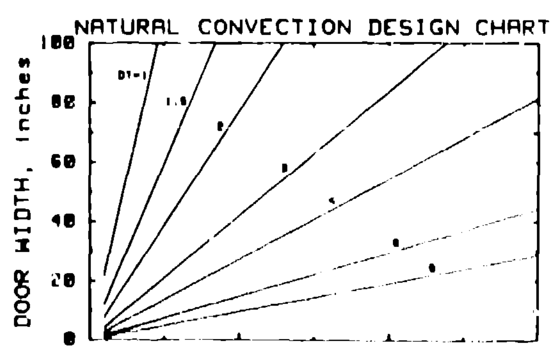

Fig. 2. Design chart for doorway width needed to heat a remote room by natural convection. The assumed door height is 6 ft 8 in.

Natural Convective Loops

A convective loop, shown in Fig. 3, is between a two-story-high sunspace and the attached two-story house. One way to describe such a loop is as a "heat engine." Heat is added in the south side of the loop, and the same amount of heat is withdrawn on the north side. Air flows around the loop because of the difference in densities between the south leg and the north leg. In fact, we can calculate the flow rate based on the difference in average temperatures between the two legs. It is also possible for heat to be removed along the top leg of the loop; this is particularly effective in driving the loop because it increases the average density along the vertical north leg. Lastly, it is possible for heat to be removed along the bottom return leg; this is not very effective in driving the loop because it does not contribute to the increased density in the north vertical leg. We have observed convective loops like this in many passive solar buildings. Normally they use only normal architectural elements, such as doorways, halls, sunspaces, rooms, and stairways without significant compromise in the livability or architectural freedom of the design.

NATURAL CONVECTION EXPERIMENTAL RESULTS

Air velocity and temperature measurements have been made in 15 buildings that incorporate natural convection involving a sunspace and other architectural features. In most cases convective loops are inadvertent; that is, they were not intentional or even perceived by the owner or designer.

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. 2, and also a set of design guidelines. Results from the first two years of experiments are summarized in Refs. 1-3. A more comprehensive description of interim results is being written and will be published as a Los Alamos report. A few of the most recent observations are given below.

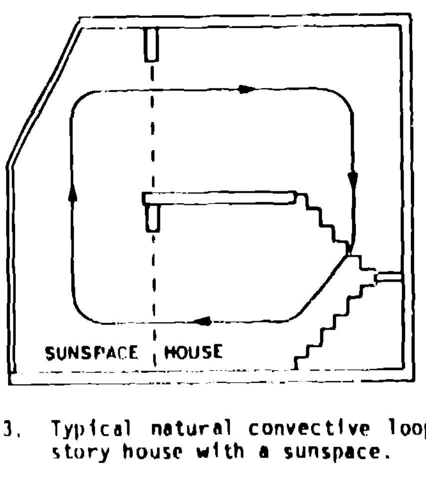

Fig. 3. Typical natural convective loop in a two-story house with a sunspace.

Observations of ΔT_d

It is important to observe the nature of the door-top-to-door-bottom temperature difference, ΔT_d, because the energy flow is proportional to it, as shown in Eq. (2). To obtain Eq. (3), we assumed $\Delta T_d = \Delta T$. We have measured both temperature differences and observe that the ratio $\Delta T_d/\Delta T$ tends to rise during the day.

Typical results are shown in Figs. 4-6 for the Bea Allen house in Albuquerque. Figure 4 shows ΔT and ΔT_d for one sunny day and Fig. 5 shows the ratio $\Delta T_d/\Delta T$. Our best estimate of the corresponding convection energy, Q, is shown in Fig. 6. The total energy transport through the 3-ft doorway is 48,770 Btu for this day. If we use Eq. (3) to calculate energy transport, the total energy transport over the day is 40,480 Btu, indicating that this equation generally underestimates the average energy transport. Thus the design chart of Fig. 2 can be expected to be somewhat conservative.

Glass Temperatures

We have also noted in all our observations that the surface of the glass in a sunspace or direct gain room is warmer than the air temperature during sunny periods. This is due to solar heating of the glass. The warm glass surface plays a major role in heating the room air. Strong rising boundary-layer flows are observed next to the glass. Figure 7 shows a comparison of glass temperature and room temperature for the Bea Allen house. The slope of the sunspace glass is 70°.

Stratification

We have observed in our experiments that temperatures in the two adjacent rooms will usually be stratified when they are linked by a convective exchange through an opening. The degree of stratification will depend on the rate of heat ex-

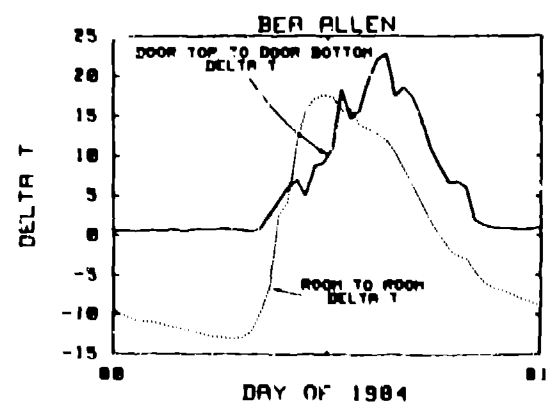

Fig. 4. Observations of the room-to-room temperature difference, measured at 60 in. above the floor and the door-top-to-door-bottom temperature difference, measured 4 in. above the floor and 4 in. below the door top in the aperture.

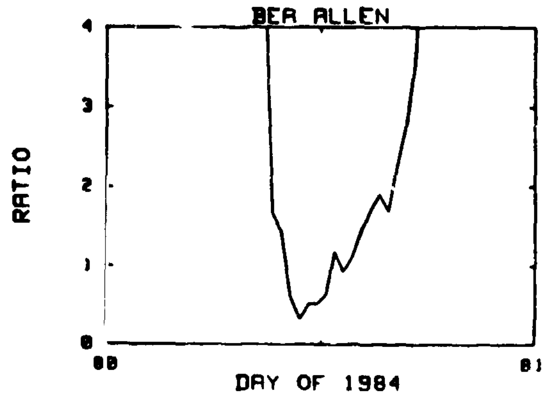

Fig. 5. Ratio of $\Delta T_d/\Delta T$, based on the data of Fig. 4.

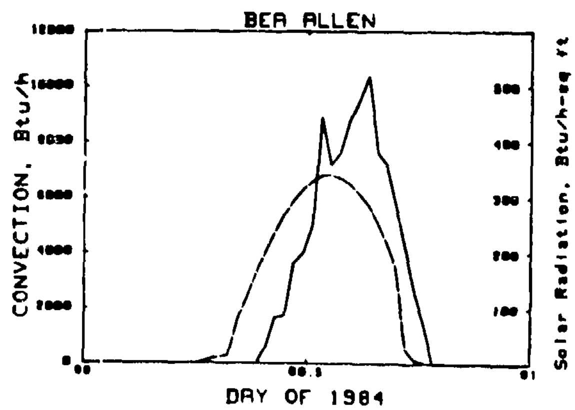

Fig. 6. Energy flow through the same doorway (solid line). The dotted line shows the solar radiation incident on the outside of the sunspace glazing; this shows the relative time lag of the convection. The sunspace is quite massive.

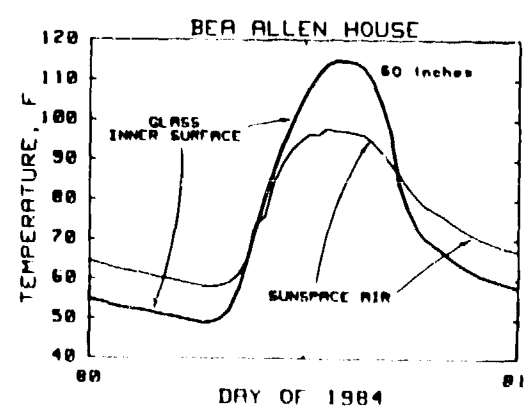

Fig. 7. Temperatures measured on the same day. The glass temperature is measured by a thermocouple attached to the inner surface of the double glazing using transparent tape. The air temperature is measured behind a small sunshade.

change. Stratification will tend to enhance the rate of heat exchange because it increases the temperature difference between the upper air stream and the lower air stream, ΔT_d. Because the flow streamlines are generally not horizontal approaching and leaving the doorway, the mixed-mean temperatures cannot be determined easily from the stratification profiles but must be measured experimentally. This has been one of the objectives of the Los Alamos experiments.

A typical stratification profile is shown in Fig. 8. This is taken in an atrium located in the center of the Ed Balcomb house in Albuquerque. In most cases, we observe strong stratification of 0.5 to 1.2°F/ft during solar-driven periods, which diminishes to nearly zero stratification at night. We believe that heat exchange by natural convection to adjacent rooms tends to promote rather than diminish stratification during the day and that flows in opposite directions on north and south walls result in mixing of the sunspace air at night.

Flow Visualization

We have been using two effective methods to help visualize airflows: smoke traces and bubbles. The smoke traces are generated using a smouldering punk stick; several of these are deployed upstream of a doorway and the ensuing trails of smoke can be followed for several feet. This has proved to be the most effective method for studying airflow patterns approaching and leaving an aperture.

Bubbles have proved to be effective for tracing airflow over longer distances. A bubble generator has been built, following a procedure developed at the Colorado State University,[4] which generates a continuous stream of helium-filled soap bubbles about 1/32 in. in diameter. The bubbles survive for several minutes and are neutrally buoyant so that they can be used to trace airflow from room to room. However, they are not useful in a sun-

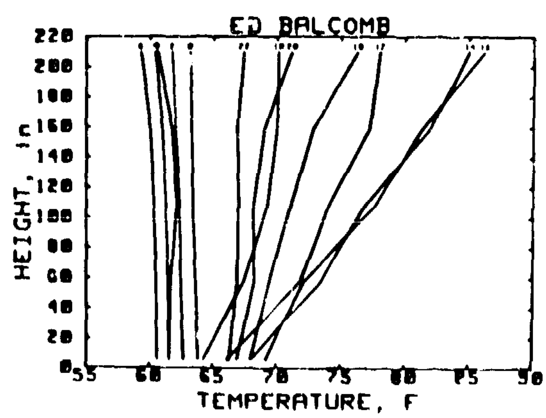

Fig. 8. Air temperature stratification measured in a central atrium in a one-story house. The atrium glazing is on the south side of a large vertical clerestory. The atrium is convectively connected to adjacent rooms of the house on all four sides and has a massive floor and north wall.

Hybrid Systems

In the course of taking measurements in 15 buildings, we have observed the operation of active forced-air elements in five of the buildings. The active systems observed are the following: A fan-forced rockbed, a fan-forced blockbed, air fan forced into a basement room, air fan forced into remote rooms on the north side of the house, and a destratification fan in the five-story atrium of a commercial building.

The quantitative results from these observations have all been discouraging, indicating performance well below that predicted by the designer. Usually the heat transfer rates achieved are 1/3 or less than the values expected.

In all cases, the reasons for the poor performance have been evident from inspection of the data. Problems include leaky ducts, inadequate insulation, inadequate heat transfer, and undersizing of equipment.

We conclude from these findings that hybrid systems are often poorly designed. It is not that the hybrid approach was not appropriate in all the cases studied, but that the design was lacking in one or another regard. As in any active system, design and implementation require good sound engineering. Although our findings have been subsidiary to the major objectives of the project, we believe they point to a general area needing more investigation.

SIMILITUDE EXPERIMENTS

Similitude experiments are used to study natural airflow in a scale-model laboratory experimental setup. By using a heavy gas, Freon, a model can be used that is roughly 1/5th scale. Experiments have been conducted at Los Alamos first by Weber[5] and then by Yamaguchi.[6] The results are presented as plots and correlations of Nusselt number as a function of Grashof number because, according to similitude theory, these results can be related directly to steady-state energy transport in air in a geometry of the same shape. Weber and Yamaguchi used the experiments primarily for the study of the effect of aperture height and width on convective exchange between two adjacent single-story rooms at the same elevation.

The similitude experiment has now been completely rebuilt and reinstrumented by Mark White, a graduate research assistant from the Colorado State University working at Los Alamos, in order to study other geometries. At the same time the design has been improved to totally eliminate Freon leaks. The geometry now permits the study of natural convection in two-story situations and the effect of level changes between rooms. The experiment has been checked to determine the heat loss calibration, and we are ready to begin convection experiments using Freon.

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