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AUTHOR(S): J. Douglas Balcomb
Kenjiro Yamaguchi

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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HEAT DISTRIBUTION BY NATURAL CONVECTION*

J. Douglas Balcomb and Kenjiro Yamaguchi**
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Natural convection between spaces in a building can play a major role in energy transfer. Two situations are investigated: convection through a single doorway into a remote room, and a convective loop in a two-story house with a south sunspace where a north stairway serves as the return path. A doorway-sizing equation is given for the single-door case. Detailed data are given from the monitoring of airflow in one two-story house and summary data are given for five others. Observations on the nature of the airflow and design guidelines are presented.

1. INTRODUCTION

Natural convection can play a major role in distributing heat throughout passive solar buildings. Remote rooms can be effectively heated by air convection through a doorway that connects the remote room to a solar heated room. Experimental results from several buildings show typical daytime convective heat flow of 1000 to 2000 Btu/h driven by temperature differences of 3 to 6°F between rooms providing adequate heat for comfort. These results are in good agreement with a simple doorway correlation equation. Convection through single doorways was found to be the major mechanism for distribution of heat from the sunspace to the house in the Balcomb solar home, accounting for transfer of 16.3 million Btu during a 6-month winter period.[1] Analysis shows that the large swings in sunspace temperature aid in this exchange. Heat storage in the materials of room surfaces was also found to be quite important.

A more complex situation concerns internal convective loops that can play a vital role in distribution of solar heat. In a typical case, heat is convected from a sunspace through upper doorways or windows into the house, through hallways, down a stairway, and returns to the sunspace through doorways at the lower level. Several Santa Fe houses that have such loops have been monitored using smoke sticks, anemometers, and thermocouples; and the data have been analyzed to determine airflows and energy flows. The flow pattern is often found to be complex, involving a main loop and several subloops.

2. SIMPLE DOORWAY CONVECTION

Convection through a doorway at a point in time can be estimated from the following relation:[2]

$$Q = 4.6\, w \sqrt{(h\, \Delta T)^3}\ , \qquad (1)$$

where Q = convection heat flow, Btu/h,
w = door width, ft,
h = door height, ft, and
ΔT = room-to-room temperature difference, °F.

This relation can be used to determine the required door width needed to supply the heat losses from a remote room by using the same equation to describe average conditions. To do this we set Q equal to the 24-hour average heat loss of the room, in which case ΔT is the 24-hour average room-to-room temperature difference.

$$w = \frac{Q}{4.6 \sqrt{(h\, \Delta T)^3}}\ . \qquad (2)$$

For example, if the average inside/outside temperature difference in January is 30°F and the loss coefficient of the room (UA) is 60 Btu/h, Q = 30 x 60 = 1800 Btu/h, average. If the maximum, tolerable, average ΔT from

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**Guest Scientist, Ohbayashi-Gumi, Ltd., 2 chome, Kanda Tsukasa-cho, Chiyoda-ku, Tokyo, Japan.

room-to-room is 4°F, the necessary width of a standard 6-ft 8-in. door is

$$w = \frac{1800}{4.6\sqrt{(6.67 \times 4)^3}} = 2.84 \text{ ft} = 34 \text{ in.}$$

Detailed numerical experiments were performed to determine the validity of the steady-state assumption under time-varying conditions using typical hourly room temperature and outside temperature measurements made in passive solar houses.[3] The conclusion of this investigation is that the ΔT given by Eq. 2 is quite close to the average room-to-room ΔT for cases of moderate room-temperature swing (for example, ΔT = 1.6°F, Q = 800 Btu/h, source room-temperature swing = 7°F.) However, if the source room-temperature swing is large, the equation tends to overpredict the average ΔT. Thus, using Eq. 2 to size doorways is a conservative approach; the ΔT achieved will be equal to or less than the tolerance value desired.

3. NATURAL CONVECTIVE LOOPS

3.1. Discussion of Principles.

A convective loop, shown in Fig. 1, 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." Figure 2 shows this schematically. 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

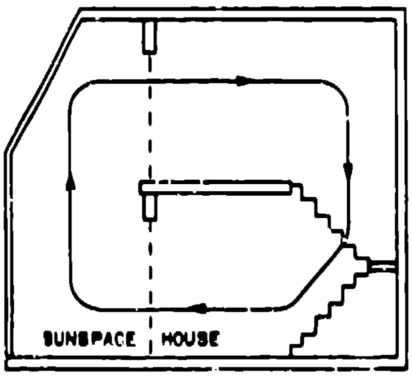

Fig. 1. Typical natural convective loop in a two-story house with a sunspace.

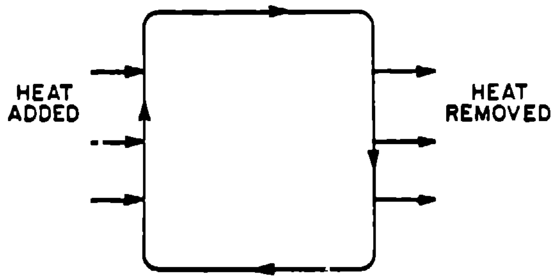

Fig. 2. "Heat engine" representation of a convective loop. The engine is the air motion, and the driving mechanism is heat added on one side and removed on the other.

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.

This paper is not concerned with the double-envelope house concept, a special case that has been much debated. It is, instead, concerned solely with loops that involve normal architectural elements within a building, such as hallways, stairways, other rooms in the building, and doorways connecting these spaces.

3.2. Summary of Convective Loop Results.

Air velocity and temperature measurements have been made in six buildings that incorporate natural convective loops involving a sunspace and other architectural features. In most cases these loops are inadvertent; that is, they were not intentional or even perceived by the owner or designer. Measurements were made near midday during relatively sunny weather; a summary of these results for six houses is given in Table I. The results, which will be reported in detail in future Los Alamos reports, have been very encouraging, indicating large convective energy exchange.

3.3. La Vereda, Model 4 Results

Typical results, shown below for the third building in Table I, were gathered in a two-story house with a linear sunspace covering the entire south facade. The house is Model 4 in the La Vereda subdivision in Santa Fe, designed and built by Communico (Susan and Wayne Nichols). Floor plans are shown in Fig. 3. Although two-way airflow occurs in every doorway, the major flow is from the sunspace into the upper level through two double doors, [7] and [8]. About half of this flow returns to the sunspace through a door at midlevel, [1] (the house is

TABLE I

SUMMARY OF CONVECTION DATA MEASURED IN SIX HOUSES

Sunspace Height	Sunspace Glazed Area	Sunspace-to-House: Connecting Doorway Area	Typical ΔT	Total Airflow	Energy Transport by Convection
# of Stories	ft^2	ft^2	^{o}F	CFM	Btu/h
2	400	80	6	1680	17700
1	180	31	3	660	2430
2	410	114	5	2240	15500
2	570	49	10	1670	21100
1.5	310	64	4	1029	5110
2	210	82	4	1190	4870

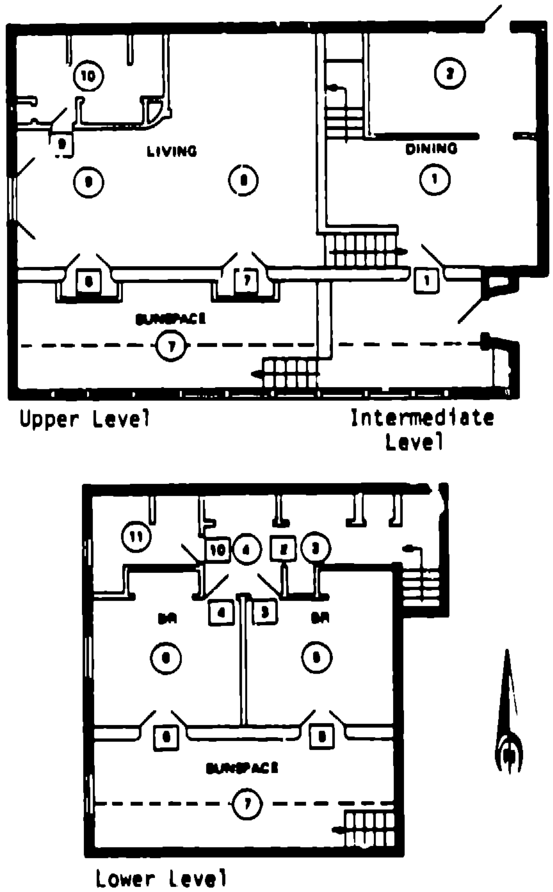

Fig. 3. Floor plans of La Vereda, Model 4. The west end is two story; and the east, entry end is single story at an intermediate level. Arrows on stairs show traffic down. Circles refer to room numbers, and squares refer to aperture numbers.

split-level), and the remainder flows down a stairway and west along the downstairs hall, 2, returning through two downstairs bedrooms, 5 and 6.

Vertical air-velocity profiles were measured in each doorway, two examples of which are shown in Figs. 4 and 5. Volumetric airflows in each direction are calculated by integrating the velocity profiles for each doorway; the results are then adjusted to achieve the necessary overall mass balances for each zone, assuming no effect attributable to outside air infiltration. These adjustments are always within the range of air velocities measured.

Air temperature profiles were also measured, and energy flows are calculated by integrating the product of air velocity times temperature. Final results for the house are shown in Fig. 6, giving airflows, velocity-weighted average temperatures, and energy flows by natural convection.

3.4. Other Buildings

Data taken in other buildings have been analyzed in the same way to obtain the results in Table I. Some of the more interesting observations are as follows:

- In one house a 2 ft^2 laundry chute in the north part of the house provides a return air path for 183 cfm of air, helping to heat a remote north bathroom.
- In another house a series of 12 1-ft-diameter ducts were intentionally installed to provide a return air path to the sunspace. A combined airflow of 406 cfm was measured passing through these ducts compared with a return airflow of 1014 cfm through a single 27-in. door opening.
- In most, but not all, cases, two-way flow is observed in the apertures.

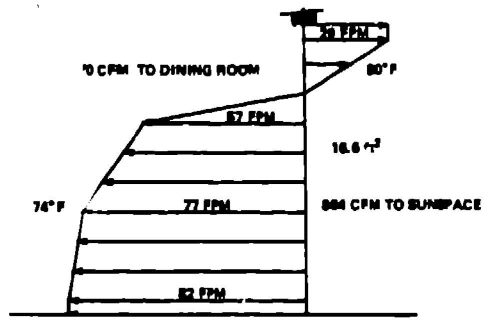

Fig. 4. Corrected velocity profile in aperture [1], located between the dining room and the sunspace.

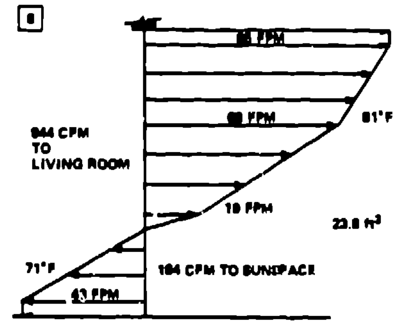

Fig. 5. Corrected velocity profile in aperture [8], located between the living room and the sunspace.

- Air stratification is pronounced in some buildings and almost nonexistent in others. This is not yet well understood.
- Warm airflow is generally across the ceiling and cold airflow along the floor, as expected.
- Different air streams do not seem to mix readily and, thus, flow to their destinations without interference. The warmest available air stream seems to flow to the coldest spot. Consequently, the airflow pattern seems to develop in a manner that will most nearly equalize the temperature distribution in the building.
- The zero-flow point in each doorway (the point where the flow velocity changes direction) is at about the same level in doorways that connect to the same large space, as expected.
- Small level changes, stepping down from north to south, help greatly in convective exchange, maintaining warmer north-room floor temperatures.
- Discomfort can be experienced in the evening if cool return air is channeled onto the feet of sitting people. This is observed in a house with a two-story Trombe wall forming the south side of the living room. Convection is driven up the Trombe wall and across the ceiling into upper-level bedrooms; air returning from these rooms collects on a balcony overlooking the living room; this cool air then funnels down the stairway and streams across the living room floor at high velocity. Floor-level perforations along the length of balcony that would allow the return air to spill into the living room at low velocity would have been a simple remedy.
- Air convection inside the Karen Terry direct-gain residence[4] was observed to be very small, with pronounced stratification. Solar gains are distributed uniformly through the building and, therefore, there is little need to move heat horizontally and, thus, little convection.

3.5. Design Guidelines

Although the work described here is still in progress, certain design guidelines emerge clearly. It is evident that a major amount of heat can be distributed and stored inside a building by convection from a sunspace. The major driving mechanism for this convection is the heat engine, driven by solar heating on one side and heat removal on the opposite side (both by heat storage in walls and daytime heat losses). If the designer is fully aware of the principles involved, the design can benefit most from effective convective exchange.

The key design factor is proper layout of the building so that convective loops can operate effectively. This can usually be done without architectural compromise. In fact, in most cases studied, no conscious attempt to achieve a convective loop was made; it resulted, strictly in serendipitous fashion, from architectural considerations.

In designing for a convective loop, the designer should make multiple use of building elements as much as possible. Do not contrive a convective loop for its own sake but rather try to work it in with normal traffic flow. The following list gives design hints for one type of convective loop, starting with the source of heat and moving around in the same direction as the airflow.

- A sunspace makes an excellent heat source to drive the convective loop because high temperatures (80°F) are available in sunny weather. Because the flow velocity varies as the square root of the height, it is desirable to make the space as high as practical. A two-story building with a two-story sunspace has been found to work effectively; greater heights would probably work even better, although the tendency for temperature to stratify might be exacerbated. A dark-colored mass wall at the back of the sunspace will aid in absorbing the solar radiation and will heat the air as it rises.

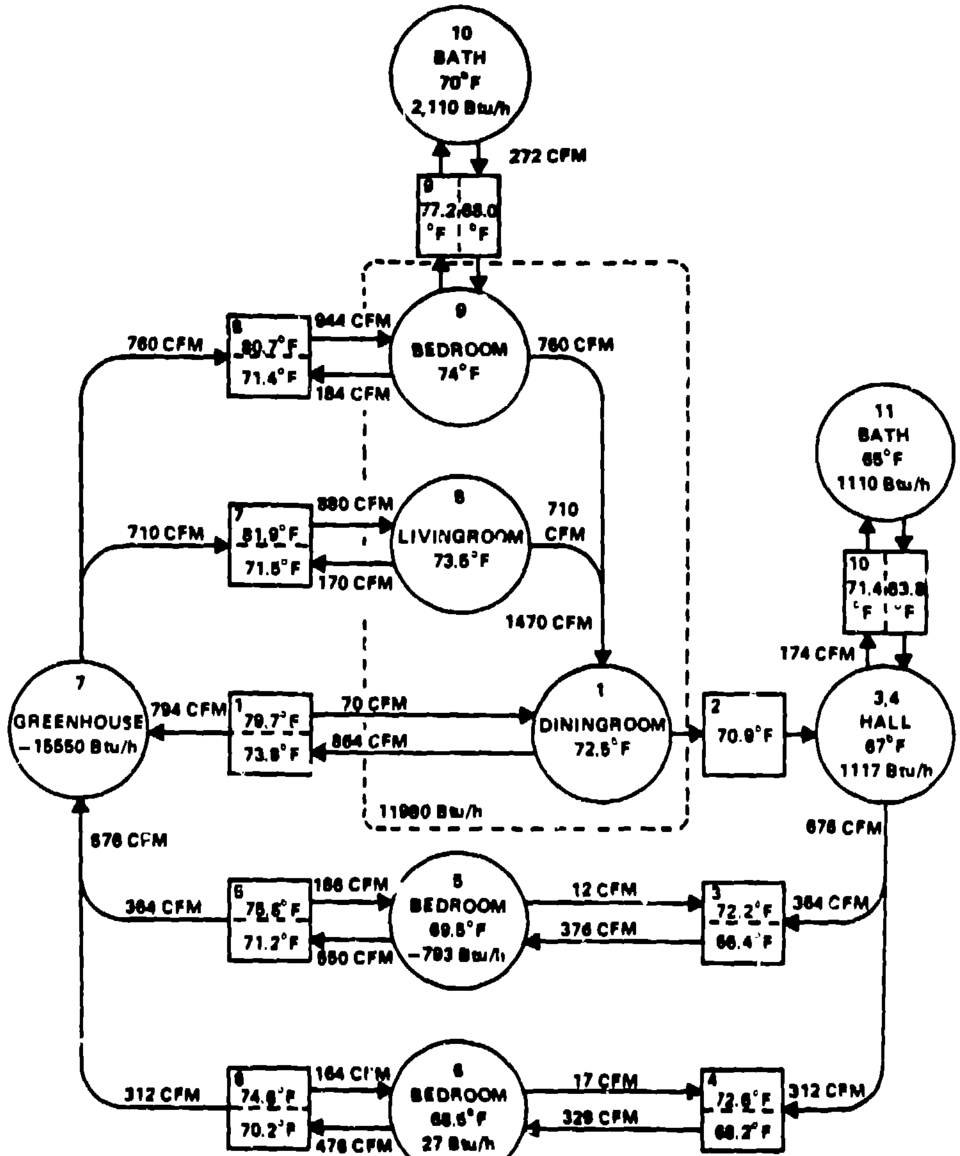

Fig. 6. Natural airflow diagram in La Vereda, Model 4, at 2:00 p.m., January 11, 1983, a sunny day. See Fig. 3 for identification numbers of rooms (circles) and apertures (squares). Airflow rates and velocity-weighted average temperatures are shown for each airflow direction for each aperture. Net energy flow rates are shown for the rooms, but note that rooms 1, 8, and 9 cannot be disaggregated so that the total energy deposited in the three rooms (11980 Btu/h) refers to the region enclosed by the dotted line. Room temperatures shown are ±1°F. Greenhouse temperatures ranged from 68°F near the floor to 82°F near the ceiling.

- Provide a large opening at the top of the sunspace for the air to enter the upper story. Doors are excellent for this purpose, although large operable windows can also be used. Doors are preferable because they are larger and are more apt to be opened during the day. A shallow balcony opening onto the top level of the sunspace is a popular design element. If vents at ceiling height are used, it is not necessary to close them during the night because closing openings at the return end will effectively shut off the loop.

- Provide for airflow across the upper level of the building from the south side to the north side. This is conveniently achieved using a hallway, although other rooms can also be used.

- Provide for downflow of air in the north part of the house; a stairwell serves this purpose ideally. The fact that the air may have to bend around corners to get across the building, down the stairs, and into the lower portions of the building is of no great concern so long as the flow area is adequate. It is desirable for this path to be against the north wall both to increase the airflow and to assure that the convective loop can effectively supply the heat loss.

- Arrange for air return through the lower floor and back into the sunspace. Again, this might be through a hallway or simply across a room. It is essential to provide a doorway that can be closed in this portion of the path. This prevents cool air from the sunspace from flowing back into the building, tending to reverse the loop at night. Windows are not effective for this purpose because they will not allow cool floor-level air to return to the sunspace.

- Provide one or more level changes at the ground floor, stepping down from the north side of the house toward the south. This makes the floor level of the sunspace the lowest point in the loop so that cool air will drain to this spot. One or two steps should be sufficient. Elevate planting beds in the sunspace.

4. FUTURE WORK

- Measurements will be made over longer periods, perhaps for several days.

- The theory will be developed to allow quantitative prediction of convective exchange in complex situations. This will be reduced to algorithms for use in computer simulation models.

- Additional design guidelines, including quantitative estimation procedures, will be formulated and transferred to the design community.

5. ACKNOWLEDGMENT

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