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TITLE: HEAT DISTRIBUTION BY NATURAL CONVECTION

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HEAT DISTRIBUTION BY NATURAL CONVECTION*

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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 or to reduce the number of 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 design guidelines 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 12 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

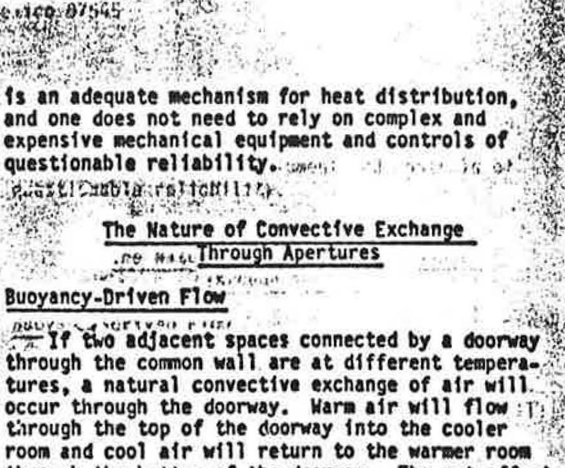

Fig. 1. Natural Airflow Velocities in a Typical Doorway with a 6°F Temperature Difference Between Rooms.

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

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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 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 are 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, therefore, 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:

$$V = 1.98\, w\sqrt{h^3\, \Delta T}\ ,$$

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,

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

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

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

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 exchange. 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.

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 5000 Btu/h and that, under these conditions, we are willing to allow an average room temperature 2°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.

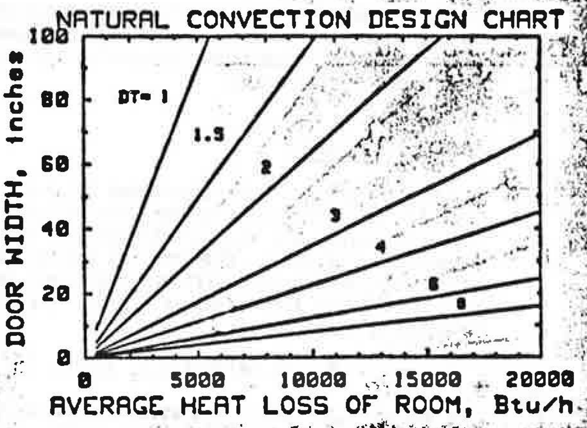

Fig. 2. Design Chart for Doorway Width Needed to Heat a Remote Room by Natural Convection. The Assumed Door Height is 6 ft 8 in.

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 t[illegible] north leg. In fact, we can calculate the fl[illegible]e based on the difference in average [illegible] between the two legs. It is also po[illegible] 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.

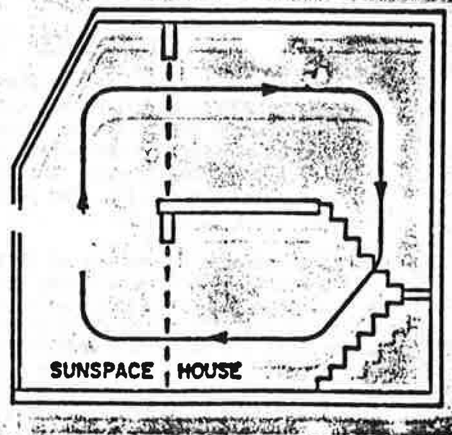

Fig. 3. Typical Natural Convective Loop in a Two-Story House with a Sunspace.

Summary of Natural Convection Results

Air velocity and temperature measurements have been made in 12 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. 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.

We have found that the observed natural convection is quite predictable using relatively simple models. In the future we plan to distill the results into simple design charts, similar to Fig. 2.

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 air flow.

- 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.

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	°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

- 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 building; 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.

Whether the building is one or two stories, it is particularly effective to provide one or more level changes at the ground floor, stepping down from the north side of the building 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.

END

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