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Natural Convection in a Passive Solar Building

Allan T. Kirkpatrick, Dallas D. Hill, and Kirk W. Stokes
Department of Mechanical Engineering
Colorado State University
Fort Collins, Colorado 80523

Abstract

Experiments are described that were conducted at the full-scale Reconfigurable Passive Test (REPEAT) facility at Colorado State University. We measured velocity and temperature profiles in the doorways between a sunspace and adjoining north rooms. The results are presented in terms of a series of velocity and temperature profiles for different times of day.

INTRODUCTION

The performance of comfortable, energy-efficient, passive solar-heated buildings depends on natural convection flow processes.

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Natural convection is a means by which thermal energy is transferred from one part of the building to another without the use of mechanical devices. The natural convection path or loop in a building usually involves flow from a heated room through a doorway to a remote room, then back to the heated room through either the same doorway or a different one. In a recent issue of *Passive Solar Journal,* Anderson (1986) reviewed natural convection research as it relates to passive solar building applications.

The driving mechanism of natural convection heat transfer is the temperature difference across the doorways between the north and south zones of a building. The temperature difference implies that the air on one side of the doorway is of a different density than the air on the other side. From the principle of hydrostatics, where pressure is proportional to density times depth, the pressure difference across the doorway varies with height. This pressure difference causes air to accelerate and convect through the doorway.

Passive solar-heated buildings, since they are strongly coupled to the radiative and convective thermal environment through the south facing glazing, can have large internal temperature differentials. The south portion of a building can be either warmer or cooler than the north portion of a building, which will create natural convection inside the building.

In this paper we examine the natural convection flow profiles through partitions or doorways in a multizone passive solar building. The objective is to show the dependence of the magnitude and direction of the natural convection on the interior stratification and surface temperatures. We present measurements of the temperature and velocity profiles in the doorways, related measurements of the thermal stratification in the zones, and the interior wall temperatures. As shown in Figure 1 we chose a common three-zone passive solar geometry: a two-story sunspace connected to upper and lower north rooms by single doorways.

Workers at Los Alamos National Laboratory have measured doorway flow profiles in passive solar buildings over the last five years, specifically Weber and Kearney (1980), Balcomb et al. (1981, 1983, and 1985), and White et al. (1985). They measured these profiles near noon on sunny days in occupied buildings. While natural convection through doorways was not always taken into account in the architectural design of the building, such convection was found to account for a major fraction of heat transfer from one part of the building to another. Researchers involved in these studies recommended that sunspaces connected to the rest of the building by doorways be considered an essential component of passive solar design. They found that passive return air ducts were unnecessary because of their small cross-sectional area relative to doorway area.

Analytical modeling of doorway flow has relied on Bernoulli's equation, which relates the velocity of the air in the doorway to the temperature difference across the doorway via a doorway discharge coefficient. Brown and Solvason (1962) performed early work in this area. Balcomb and his coworkers generally use the Bernoulli's equation approach to correlate the observed heat transfer through doorway openings with the temperature difference across the openings.

Since the thermal environment of a passive solar building is not constant, one would expect that the flow profiles in the doorways between zones are also not constant. The largest flow rates, of course, would be expected at solar noon at maximum solar power because of the relatively low thermal capacitance of the air. However, prior to our work, no measurements of the flow profiles at other times of the day had been done. Such measurements would help assess the daily performance of the passive solar heating components. In addition, measurements of the flow profile through the doorway in the horizontal direction have not been previously reported.

DESCRIPTION OF EXPERIMENT

The experiments were performed in the full-scale Reconfigurable Passive Test (REPEAT) facility at Colorado State University. This research facility is designed to study the thermal performance of two-story, large residential, or small commercial passive solar buildings. The facility is 10 m (33 ft) on a side, and 7 m (23 ft) high. For these experiments the building was configured into three zones: a two-story sunspace and an upper and lower north room as shown in Figure 1. The sunspace and north rooms are connected by

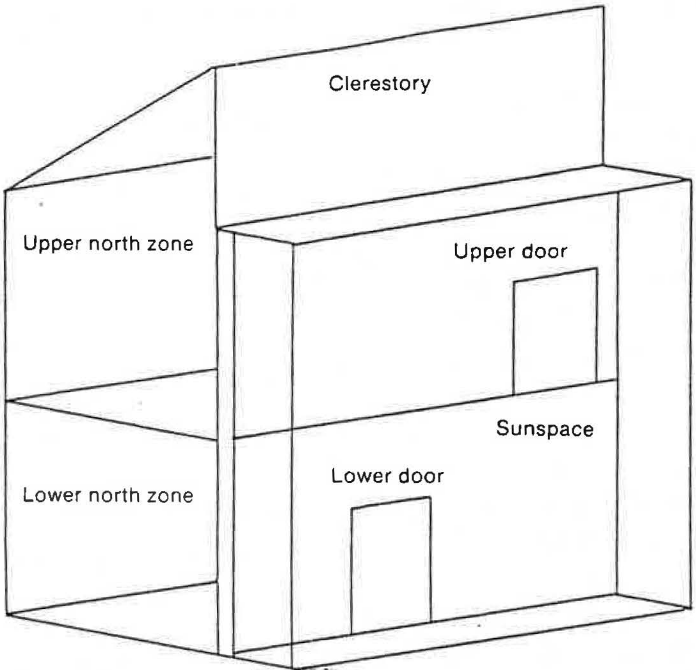


Figure 1. Building schematic of the REPEAT facility, Colorado State University

single doorways in a 20 cm (8 in.) thick brick storage wall. The doorways are 2.02 m (6.6 ft) high and 0.71 m (2.3 ft) wide, so the total doorway area is 2.87 m^2 (30.9 ft^2). The doorways were always open during the tests. The sunspace has 80 m^2 (860 ft^2) of south-facing glass. The upper north zone has 17 m^2 (180 ft^2) of south-facing clerestory glazing, with the rest of the interior surfaces being conventional gypsum wall. The upper and lower north zones are connected by a horizontal opening of the same area as a doorway, which was designed to model a stairway. The thermal capacitances of the upper and lower north zones differ greatly because the lower north walls and floor are composed of 25 cm (10 in.) thick concrete and the upper zone is of lightweight wood frame construction.

We measured the air temperatures in each zone by arrays of shielded thermocouples. The shields are concentric aluminum cylinders approximately 10 cm (4 in.) long and 5 cm (2 in.) in diameter. Thermocouples embedded in the surfaces measure the interior surface temperatures of gypsum, concrete, and glass. We used a Datametrics hot wire anemometer, which was calibrated periodically in a low speed wind tunnel, to measure the doorway velocity profiles.

Doorway temperature profiles were measured with a thermocouple. An adjustable ringstand support held the hot wires and thermocouples in place. We took data every 20 cm (50 in.) on the vertical centerline of each doorway. The uncertainty in the velocity measurements is 0.02 m/s (0.07 ft/s). The absolute uncertainty in the temperature measurements is 0.1°C (0.2°F). The data acquisition sequence began at the bottom of the upstairs doorway grid and finished at the top of the downstairs doorway grid. We did not take data in the horizontal opening. Each acquisition period lasted approximately 10 minutes. An HP3497A microvoltmeter connected to an HP86 computer collected the data.

RESULTS

We measured the velocity and temperature profiles in the doorways and zone air and surface temperatures over the course of a month in the late spring. During this time, the sun did not shine directly into the sunspace because of the overhangs. The glass, brick wall, and floor of the sunspace were heated by the diffuse solar radiation. Measurements were taken at hourly intervals.

The diagrams in Figure 2 show the general behavior of the three-zone geometry. Each diagram represents the thermal state of the building at a particular time. The solid line is a cross section of the building, the dashed lines in the doorways represent the temperature and velocity profiles, and the dotted lines in the center of each zone represent the temperature profile in the zone. Three temperature scales are shown for the north zone, doorway, and sunspace, respectively. The velocity scale is plotted along the top of the building. Also shown are the interior surface temperatures.

At 5:30 a.m. just before sunrise, as shown in Figure 2a, the flow through each doorway is unidirectional, forming a natural convection loop in the building. The flow profile in the upper doorway is similar to a slug profile, and the flow profile in the lower doorway is like a horizontal wall jet. The thermal stratification in each doorway is small. The unidirectional motion of the air can be explained in terms of the temperature difference between the north and south walls. Note that the diagrams in Figure 2 are labeled with eight surface temperatures. The temperature of the surface of the north

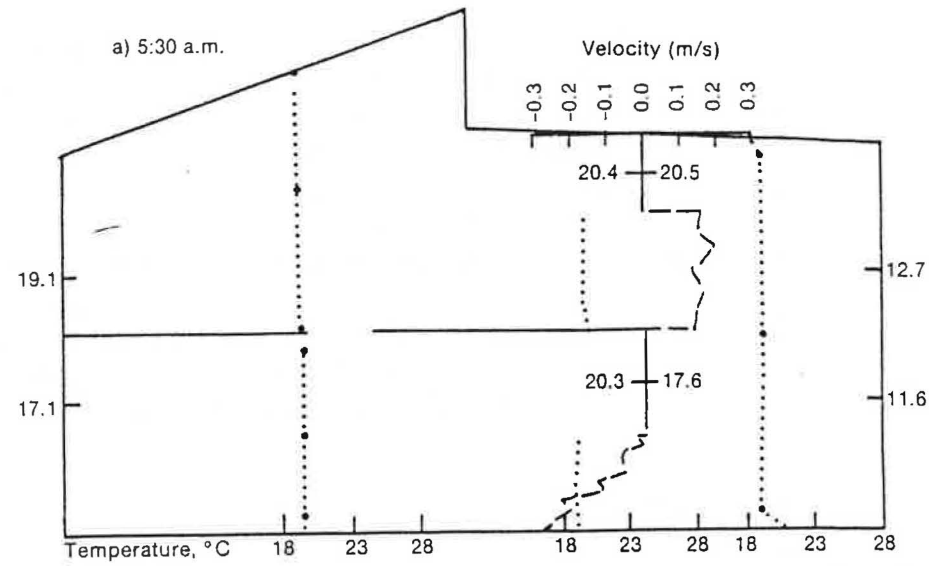


Figure 2a. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles.

wall, both at the first and second story, is about 18°C (64°F); and the temperature of the inside of the glazing of the two-story sunspace is about 12°C (54°F). So, the entire south side of the building can be considered relatively cold, and the entire north side can be considered relatively hot. This is the classical enclosure with differential heating from the side, which produces unidirectional flow as seen in the doorways. The region of zero velocity, defined as the neutral plane, is located somewhere between the two doorways.

At about an hour after sunrise at 6:30, the flow velocities are near zero, and by 8:30 a.m., the flow has reversed. As shown in Figure 2b, the flow through each doorway is unidirectional, but in the opposite direction. The flow loop is now counter-clockwise. Both flow profiles are similar to horizontal wall jets. The largest velocities in the upper door are at the top. The flow is being driven by the temperature difference of about 6°C (11°F) between the upper sunspace glazing and the lower north zone wall. The stratification in the sunspace is about 2°C (4°F), while in the taller north zones, it is about 3°C (5°F). The stratification is generally linear, and in the two north zones, it is offset. Note that the floor of the lower north zone and the sunspace is cooler than the air above it, and the ceiling of the upper north zone and the sunspace is cooler than the air below it.

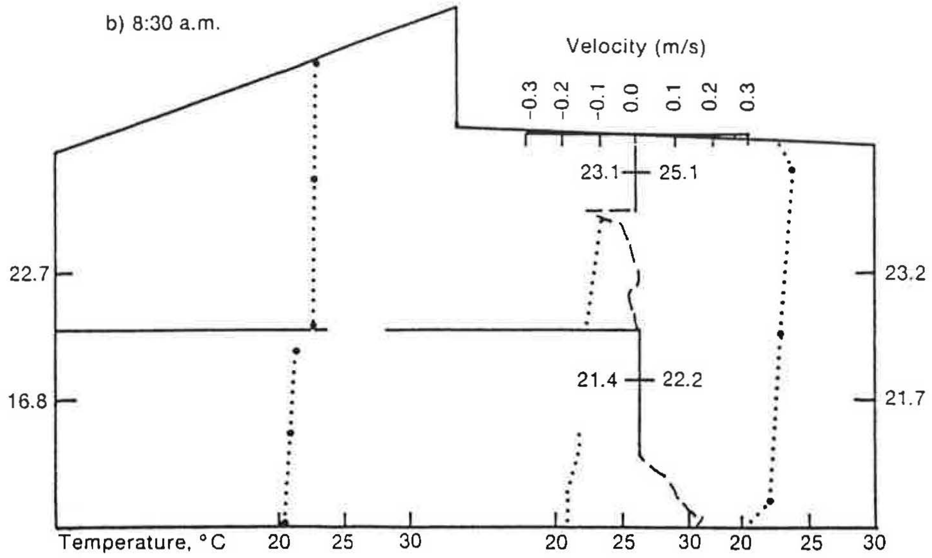
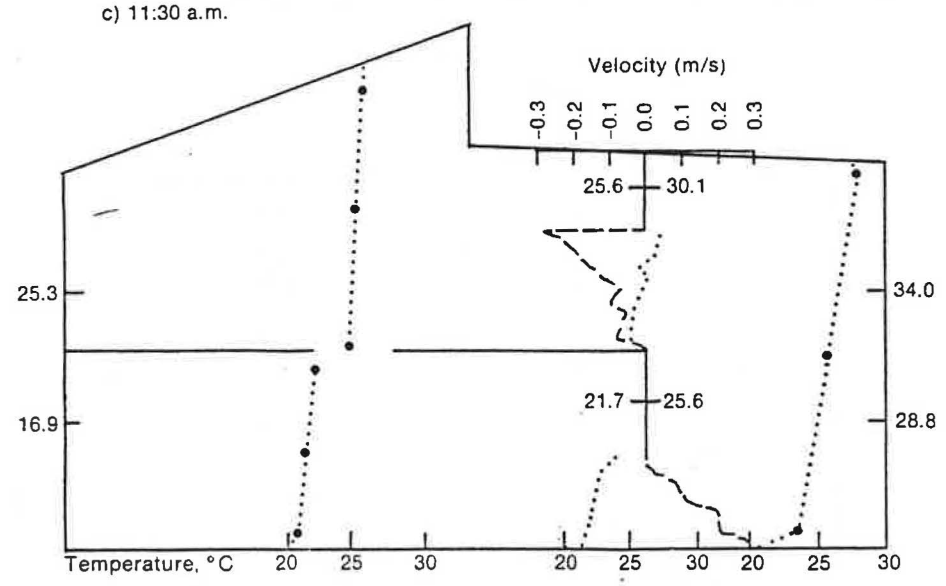


Figure 2b. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

During the morning the magnitudes of the flow velocities and the thermal stratification in the doorways increase. The thermal state of the building at 11:30 a.m. is shown in Figure 2c. The entire south glazing is now warmer than the entire north wall, which accounts for the strong counter-clockwise flow. The net heat transfer from the sunspace is about 800 W (2700 Btu/h). The temperature difference between the upper glazing and the lower north wall is 17°C (31°F). The thermal stratification in the sunspace is primarily linear, at about 4°C (7°F), while it is 5°C (9°F) in the north zones.

Maximum solar power is reached around noon. The thermal state of the building at 1:30 p.m. is shown in Figure 2d. The overall flow pattern is still generally in the counter-clockwise direction. The flow in the upper door is still unidirectional, with the velocity increasing at the bottom of the door. The flow in the lower door is now slightly bidirectional. The net heat transfer from the sunspace is about 600 W (2000 Btu/h). Because of the clerestory and the small thermal capacitance of the upper north zone wall, the temperature of the upper north zone wall has risen significantly higher than the lower north zone wall. The flow is now being driven by the temperature difference between the entire south glazing and the lower north wall. The stratification in the sunspace and the north zones is about



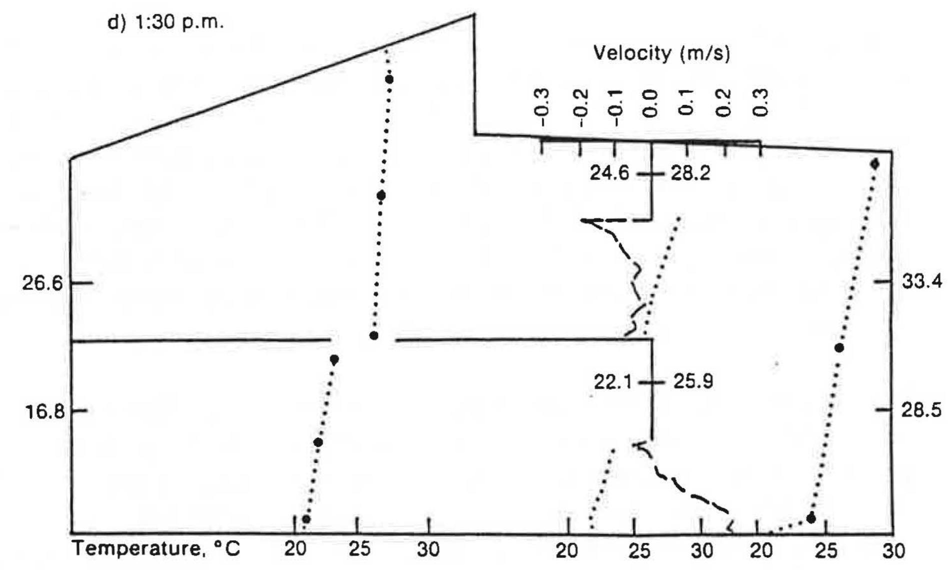


Figure 2c&d. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

5° and 6°C (9° and 11°F), respectively. A neutral plane is now located in the bottom doorway.

The temperature and flow profile at 4:30 p.m. are shown in Figure 2e. The flow through both doorways has decreased, but is still unidirectional. The bottom doorway has a jet-like profile, and the upper doorway has a curious u-shaped profile. The south glazing temperature is cooler relative to earlier readings. The stratification in the sunspace is now 4°C (7°F), and has remained constant at about 6°C (11°F) in the north zones.

Finally, the thermal state at 7:30 p.m. is shown in Figure 2f. Bidirectional profiles now exist in both doorways, clockwise for the upper door and counterclockwise for the lower door. Note that the highest and lowest interior surface temperatures are on the same wall, namely the north wall, with the south glazing and storage wall temperature somewhere in between. The flow loops in the upper and lower north zones appear to be separate from one another. The stratification in the sunspaces and the north zones is about 3°C (5°F). There are now two neutral planes, one in each doorway.

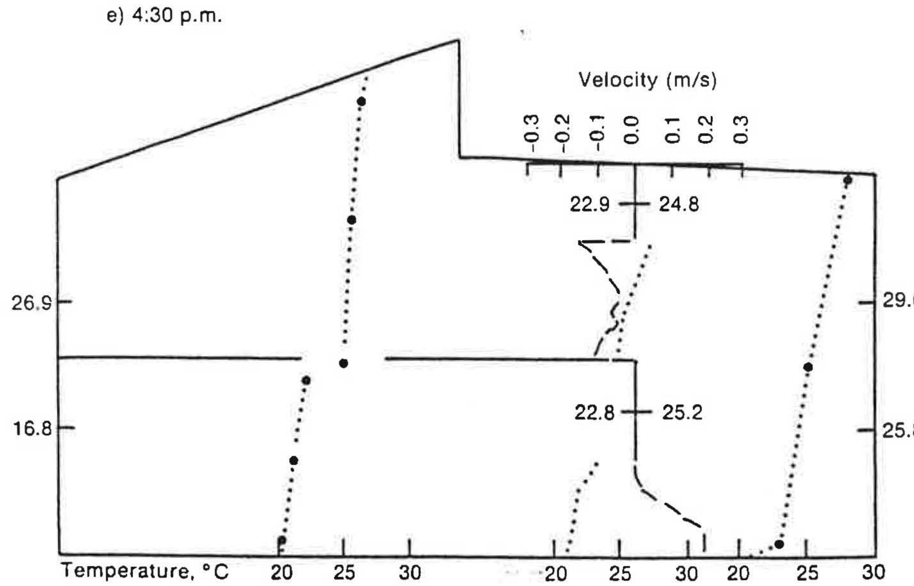


Figure 2e. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

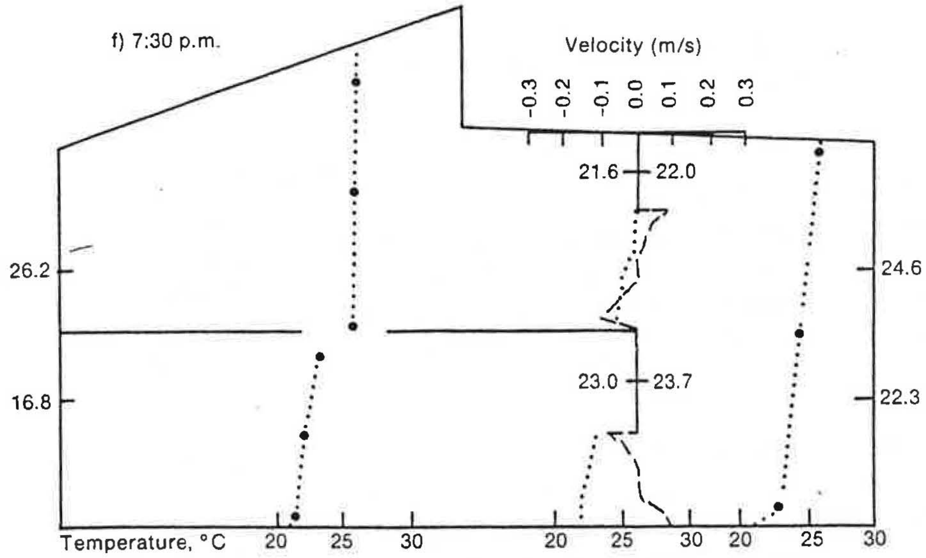


Figure 2f. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Concluded)

The thermal stratification in the doorways for the six times shown is usually slightly steeper than the stratification in the upstream zone because of the compression of the streamlines through the doorway.

Figures 3a and b show three dimensional plots of the velocity profiles versus time. The figures illustrate the changing nature of the flow profiles through the doorways during the day. The maximum flow velocities through the doorways range from 0.1 to 0.3 m/s (0.3 to 1.0 ft/s). The largest flow rates are near noon because of the relatively low thermal capacitance of the air.

Figure 4 shows the variation of the velocity through a doorway in a horizontal plane. These velocities were measured at five different heights in the lower doorway. The velocity profile in a horizontal plane is not constant, but varies by about 10%. The maximum velocity is not necessarily at the centerline; in fact, the centerline velocity is slightly smaller than the velocity on either side of it. This is probably due to the combined effect of the natural convection boundary layers and zonal flow. The average velocity obtained by integrating the velocities across a horizontal location is also shown. Note that the average velocity is either slightly greater or less than the centerline velocity.

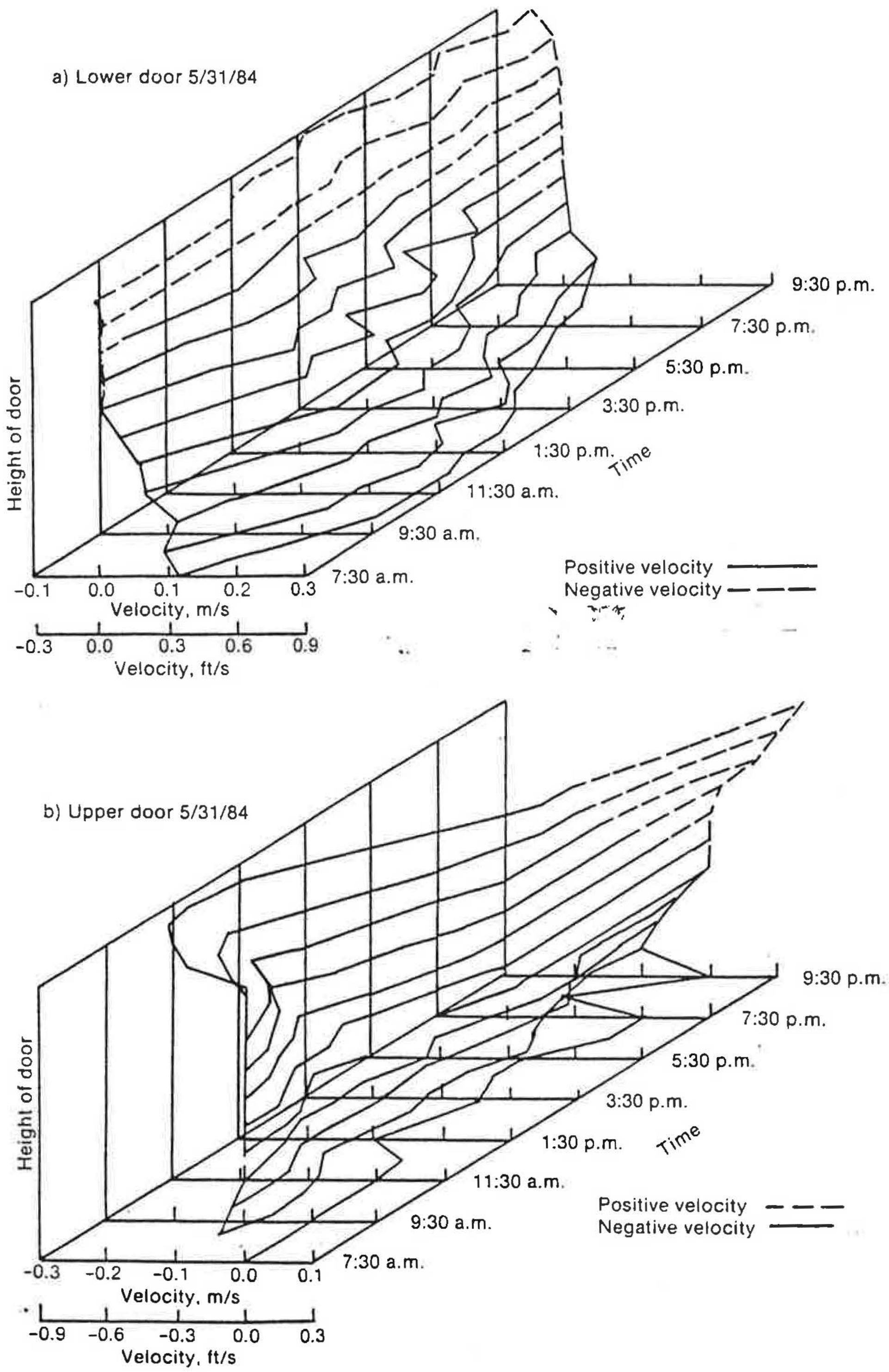


Figure 3. Velocity profile versus time for the lower doorway

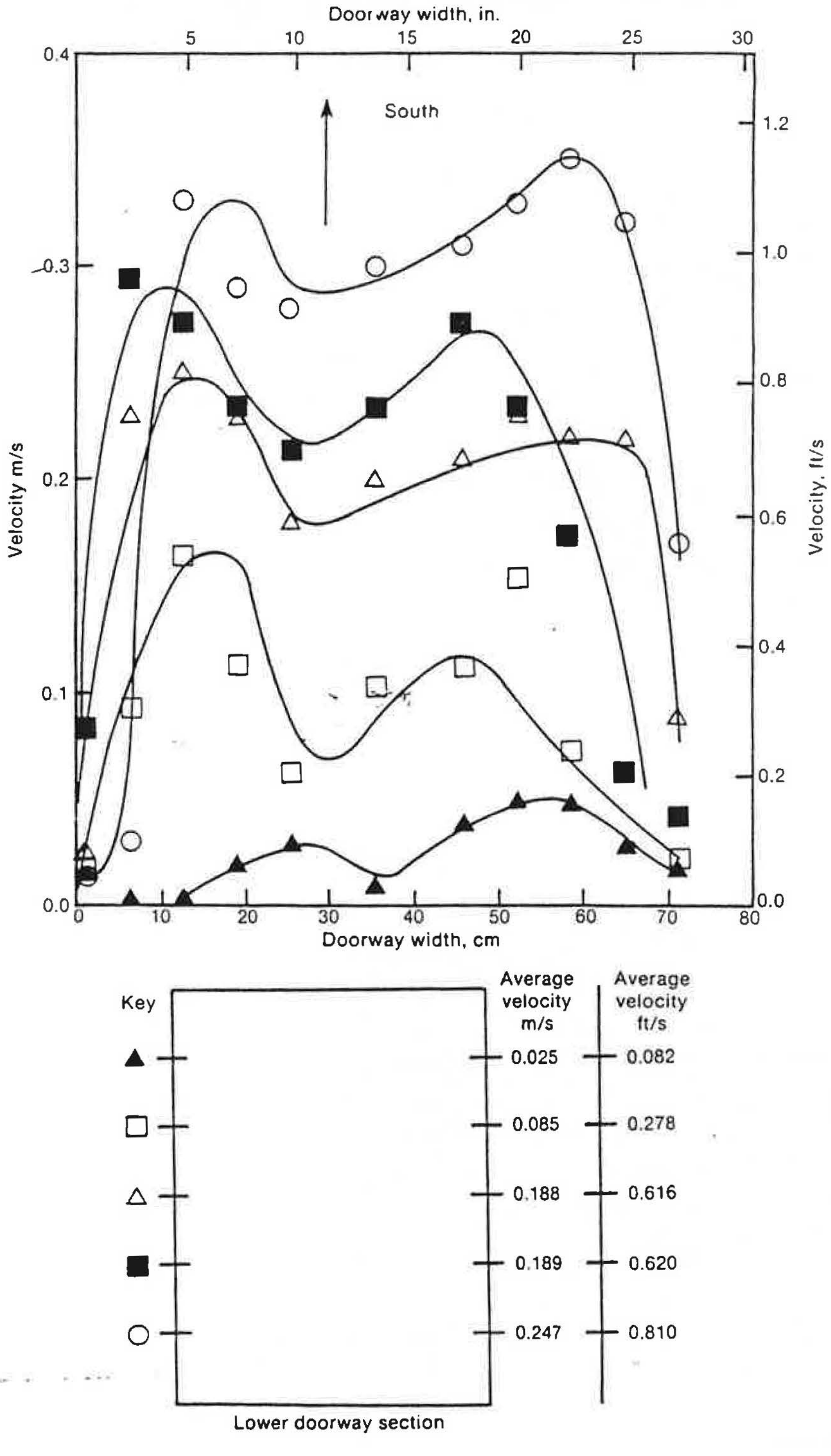


Figure 4. Horizontal velocity profiles in the lower doorway

The doorway velocity and temperature profiles can be integrated to give the net convective heat transfer from the sunspace to the rest of the building. This information is contained in Hill, Kirkpatrick, and Burns (1986), in which the Bernoulli equation approach was extended to include multiple openings and stratified zones. They correlated the net heat transfer with the temperature difference across the doorways. Fisher, Bohn, and Anderson (1985) have compared these REPEAT doorway velocity profiles with scale model simulation and correlated the doorway velocity profiles with the north and south interior wall temperatures.

CONCLUSIONS

The natural convection flow profiles through the doorways of a full scale building are complex and change in time. The flow profiles through the doorway can be both unidirectional and bidirectional. The magnitude and direction of the flow can be interpreted in terms of the relative temperatures of the north and south walls of the building.

ACKNOWLEDGMENTS

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REFERENCES

Anderson, R. 1986. Natural convection research and solar building applications. *Passive Solar Journal* 3(1):33-76.

Balcomb, J.D. 1981. Heating remote rooms in passive solar buildings. *Solar World Forum: Proc. International Solar Energy Society Congress.* (Brighton, England, Aug. 23-28, 1981) Oxford: Pergamon Press, pp. 1835-1839.

Balcomb, J.D., and G.F. Jones, 1985. Natural convection airflow and heat transport in buildings: experimental results. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 88-92.

Balcomb, J.D., and K. Yamaguchi, 1983. Heat distribution by natural convection. *Proc. 8th National Passive Solar Conf.* (Santa Fe, NM, Sept. 7-9, 1983) Boulder, CO: ASES, pp. 289-294.

Brown, W.G, and K.R. Solvason, 1962. Natural convection through rectangular openings in partitions. *Int. J. Heat Mass Transfer* 5:859-868.

Fisher, E., M. Bohn, and R. Anderson, 1985. Model simulation of building air flow: comparison with the CSU REPEAT facility. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 99-104.

Hill, D., A. Kirkpatrick, and P. Burns, 1986. Analysis and measurements of interzonal natural convection heat transfer in buildings. *J. Solar Energy Engineering* 108(3):178-184.

Weber, D.D., and R.J. Kearney, 1980. Natural convection heat transfer through an aperture in passive solar heated buildings. *Proc. 5th National Passive Solar Conf.* (Amherst, MA, Oct. 19-26, 1980) Newark, DE: AS/ISES, pp. 1037-1041.

White, M.D., C.B. Winn, G.F. Jones, and J.D. Balcomb, 1985. The influence of geometry on natural convection in buildings. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 75-81.