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NATURAL CONVECTIVE HEAT TRANSFER THROUGH AN APERTURE IN PASSIVE SOLAR HEATED BUILDINGS*

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ABSTRACT

The heat transfer through doorways by natural convection has been measured in a similarity model experiment and in two buildings of greatly differing geometry. The heat transfer can be expressed as a simple function of doorway geometry and any one of several temperature differentials.

1. INTRODUCTION

Brown and Solvason[1] have described the natural convective heat transfer through an aperture in terms of the Nusselt (Nu), Grashof (Gr), and Prandtl (Pr) similarity numbers[2] with a relation of the form

$$\frac{Nu}{Pr} = \frac{C}{3} \, Gr^{s} \; . \qquad (1)$$

Their data suggest that s is 0.5, while the coefficient of discharge, C, is in the range $0.65 \leq C \leq 1.0$. If the characteristic length is taken to be the height of a doorway, d, then for air near 70°F, Eq. 1 can be written as

$$\dot{q}_a = (15.4) \, \frac{wC}{3} \, (d \, \Delta T)^{1+s} \; . \qquad (2)$$

Here, $\dot{q}_a$ is the convective heat transfer in Btu/h, w and d are the doorway width and height in feet, and ΔT is a temperature differential in °F.

This work consists of two parts. Part I investigates the suitability of d as a characteristic length and determines several easily measurable temperature differentials that permit Eq. 2 to be used. This analysis uses data from a similitude model experiment[3] because the experiment provided data measured under carefully controlled conditions over a range of temperature differentials for four doorway heights.

The Freon gases used in the similitude experiment couple radiatively to the walls (unlike air). For this and other reasons, the temperature distributions that drive the convection may differ in actual buildings from those in the model. Therefore, Part II of this paper presents the results of full-scale tests that determine the constants C and s under extreme variations of heat source and sink configuration that may be of interest to designers.

2. PART I: EVALUATION OF CHARACTERISTIC TEMPERATURE DIFFERENTIALS

Three previous experimental studies[1,3,4] of this problem used different characteristic temperature differentials in their similarity number calculations and, therefore, have not produced consistent results. Brown and Solvason[1] used the difference in average temperature of two rooms separated by an aperture not exceeding one square foot of area. Shaw[4] used the difference in average temperatures of the upper and lower halves of the aperture. The first analysis of the similitude data[3] used the difference in volume-weighted average room temperatures. A more detailed analysis of the similitude model data follows.

3. SIMILITUDE MODELING STUDY

The similitude study used a geometrically scaled-down model (scale factor, 5.65) of a passively heated building (see Fig. 1) having two identical rooms separated by a partition containing a doorway. This model used Freon 12 as the working fluid to determine the dependence of $\dot{q}_a$ on a ΔT and doorway geometry. The model had an electrically heated vertical plate (simulated thermal storage wall) on one end and a water-cooled vertical plate (simulated thermal loss) on the other end.

*Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

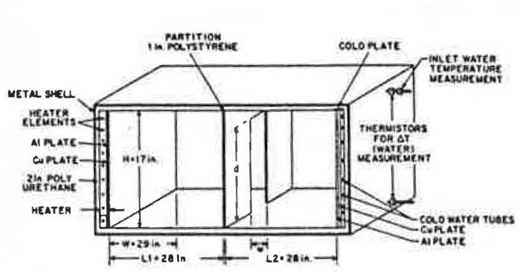

Fig. 1. Similitude model of a two-room passive solar heated building used for determining natural convection heat transfer $\dot{q}_a$ through the doorway.

Fluid temperatures were measured by a grid of 25 thermocouples capable of scanning 90% of the internal volume of the model, and $\dot{q}_a$ was calculated by subtracting conduction heat losses through the model walls from heat applied to the electric heater. This $\dot{q}_a$ calculation technique was calibrated using a partition without an aperture. Heat loss coefficients for the walls were experimentally determined from six different heating situations. Using these coefficients, heat flow could be calculated to within 1%.

Direct radiation heat transfer was eliminated because Freon 12 is opaque to thermal radiation at the system operating temperatures. The model was hermetically sealed to prevent infiltration.

Measurements were made over a range of power inputs for four different doorway heights corresponding to 96, 79, 57, and 44 inches for a full-scale building. For each measurement, 180 temperatures were recorded, and $\dot{q}_a$ was calculated. Similarity numbers were calculated for each measurement for about 50 different definitions of ΔT. Doorway height, d, was taken as the characteristic length, and a linear regression was made for each curve representing a different definition of ΔT.

The criteria used to select a characteristic ΔT were the ease of measurement, the continuity of results for all four doorway heights, and a fit (R^2 value) of a linear regression to this curve greater than 0.90 (where 1.0 is perfect).

Of the approximately fifty different definitions of ΔT that were tried, three are presented here. As indicated by Fig. 2, the first definition, ΔT_{r1} (where r refers to room-to-room) was taken to be the average of the weighted difference of the temperatures measured by thermocouples on rakes B(2) and B(3). The weight factor (w_i) of the ith thermocouple pair was determined according to the fraction of doorway height covered by the span extending half the distance to vertically neighboring thermocouples. Any measurements above the doorway height were excluded, and Σw_i was normalized to unity. Brown and Solvason[1] used similar measurements, but did not weight according to doorway height.

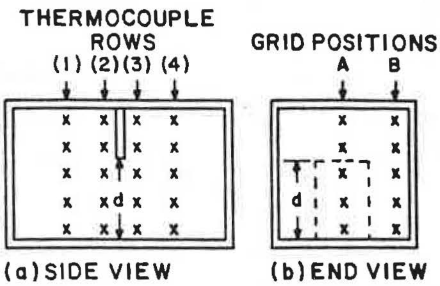

Fig. 2. Similitude model showing thermocouple locations used for ΔT calculations. Grid position A was used for ΔT_a and position B was used for ΔT_{r1} and ΔT_{r2}.

The second, ΔT_{r2}, was calculated identically to ΔT_{r1} but using rakes B(1) and B(4).

The third, ΔT_a (a indicates aperture), was taken as the difference between the average temperature of the top and bottom halves of the doorway. For the measurements used here, temperatures were not measured directly in the doorway; therefore, thermocouples of equal height on rakes A(2) and A(3) were averaged to approximate the temperature at the corresponding height in the aperture. A linear regression was then made (see Fig. 3) of temperature vs height above floor, again excluding thermocouples above the

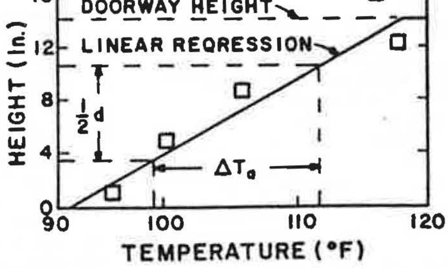

Fig. 3. Graph description of the method used to calculate ΔT_a. The points (□) are calculated doorway temperatures. Linear regression uses only points below the doorway top.

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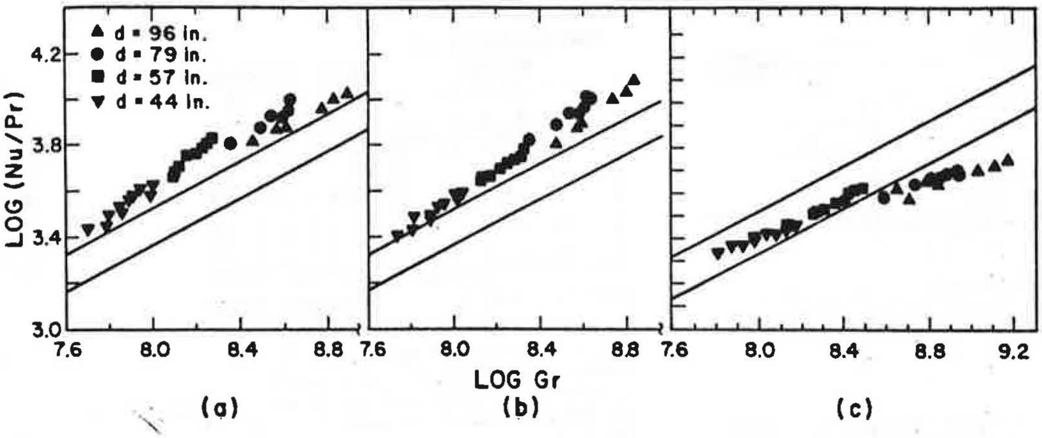

Fig. 4. Fig. 4a, 4b, and 4c are results of similitude model tests using ΔT_{r1}, ΔT_{r2}, and ΔT_a, respectively. Doorway heights (d) have been scaled to those corresponding to a full-scale structure. The upper and lower lines in each graph represent the values of Eq. 1, given by s = 0.5, and C = 1.0 and 0.65, respectively.

doorway; ΔT_a was taken to be the slope of this curve multiplied by half the doorway height. An independent test of this method using thermocouples directly in the doorway showed less than 1% difference in the resulting Nu and Gr numbers.

4. RESULTS OF SIMILITUDE EXPERIMENTS

Figures 4a, 4b, and 4c show the curves representing Eq. 1 using ΔT_{r1}, ΔT_{r2}, and ΔT_a for the characteristic temperature differential, and the doorway height d for the characteristic length. These temperature differentials result in curves for the four doorway heights with acceptable continuity and fit ($R^2 \leq 0.95$). The curve fit of ΔT_{r2} ($R^2 = 0.98$) is slightly better than that for ΔT_{r1} ($R^2 = 0.95$). However, ΔT_{r1} is easier to measure in rooms having irregular geometries, so that it was selected for the room-to-room ΔT (henceforth designated ΔT_r) for the full-scale tests.

The curve for ΔT_a shows a shallower slope (s = 0.30 compared to 0.5 and 0.6 for ΔT_{r1} and ΔT_{r2}), and the Nusselt number is lower than for the other definitions of ΔT for the entire range of Grashof numbers. However, because ΔT_a most directly measures the temperature of the air that participates in the convective heat transfer, it was also measured in the full-scale tests.

5. PART II: FULL-SCALE TESTS

Two full-scale structures having widely differing room geometries and modes of heating were instrumented to test the results of Part I. Both buildings consisted of two rooms connected by a doorway through which $\dot{q}_a$ was calculated from measurements of temperature and air velocity in the doorway. Temperatures were measured in the center of the doorway with a vertical rake of thermocouples, and air velocities were measured at 13 locations with a low velocity anemometer (DISA Type 55D80). The heat transport $\dot{q}_a$ was obtained by evaluating the sum

$$\dot{q}_a = C_p \sum_{i=1}^{13} \rho_i A_i v_i T_i \ ,$$

in which C_p is the heat capacity, and ρ_i, A_i, v_i, and T_i the density, area, velocity, and temperature at the ith measurement location. Note that v_i is negative over approximately half the total doorway area. Additional identical thermocouple rakes were located in positions corresponding to thermocouple rows B(2) and B(4) in the similitude model.

6. GHOST RANCH ATTACHED GREENHOUSE

An adobe building at Ghost Ranch, NM, that was heated by an attached greenhouse was used for the first full-scale tests. This structure consisted of two guest rooms, each having an attached greenhouse on the south side connected by an 80-in.-high doorway. At the time the tests were conducted, the greenhouse was in need of repairs and was very leaky. The infiltration rate of the structure is unknown, but was much higher than that for an average well-constructed home.

A series of eight measurements were taken, starting at early morning, to obtain a range of temperature differentials from

0° to about 15°F. This was done for two doorway heights, 80 and 56 in., to test the doorway height as a characteristic length in the Grashof and Nusselt numbers.

7. TWO-STORY LABORATORY

A series of 15 measurements were taken at a two-story laboratory with adjoining single-story office. Here, the room geometry was vastly different from that of Ghost Ranch. The building consists of a small office room connected to a large two-story laboratory by an 84-in.-high doorway. The office is well insulated; however, the laboratory is not insulated and has large infiltration rates. The office was heated by four electric space heaters. A range of ΔT from 0° to 22°F was obtained by use of combinations of these heaters.

8. RESULTS AND DISCUSSION

Results of all full-scale measurements are shown, together with similitude model data for both ΔT_a and ΔT_r in Figs. 5a and 5b. Omitting two-story data for ΔT_r, we find that the curves fall within the theoretical limits, and the slopes (s) for ΔT_a and ΔT_r are 0.49 and 0.48, respectively. Setting s = 0.5 for these curves, the values of C for ΔT_a and ΔT_r are 0.78 and 0.89, respectively.

Compared to the full-scale curves for ΔT_a, the similitude model curves have a shallower slope (s = 0.3 as opposed to 0.49 for full scale) and show lower heat transfer for a given Grashof number. These data are supported by additional measurements that were made using Freon 13, 13B1, and 114. One possible explanation is that the heated and cooled end walls of the model, together with well-insulated side walls, cause a different configuration of convection currents in the model than occur in these particular full-scale buildings. In the buildings used here, heat losses were large due to air infiltration and poor insulation. These losses caused the heated air that was convected through the doorway to the cooler room to be rapidly cooled, thereby possibly allowing a greater $\dot{q}_a$ for a given ΔT_a.

The curves corresponding to ΔT_a and ΔT_r for Ghost Ranch data are about the same and agree with Eq. 1 with s approximately 0.5. When ΔT_a is used for the two-story data again, Eq. 1 is followed with $s \sim 0.5$. However, when ΔT_r is used, the curve through the two-story data approximates a line of zero slope. This means Nu is independent of ΔT_r, or that $\dot{q}_a$ is directly proportional to ΔT_r.

In the two-story geometry, heated air from the small office is being transported to the large two-story laboratory, where it is essentially never returned. Effectively, an infinite supply of cooler air is supplied to the office. This decouples the system, and the effect is to allow maximum heat transfer by natural convection for a given doorway geometry through the aperture. This is the opposite case from the similitude model, where all the fluid is returned directly because the model is hermetically sealed.

Results from previous workers[1,4] are shown in Fig. 6. Brown and Solvason used a temperature differential similar to ΔT_r, but did not weight according to aperture height. Shaw used a form of ΔT_a, but his definition was not specified. Both workers used the aperture height as the characteristic length. Their results do not show agreement with Eq. 1. In Brown and Solvason's case, this could be because they did not weight their averages, and in Shaw's case, it may have been caused by the forced-air system that they used to maintain temperature differences.

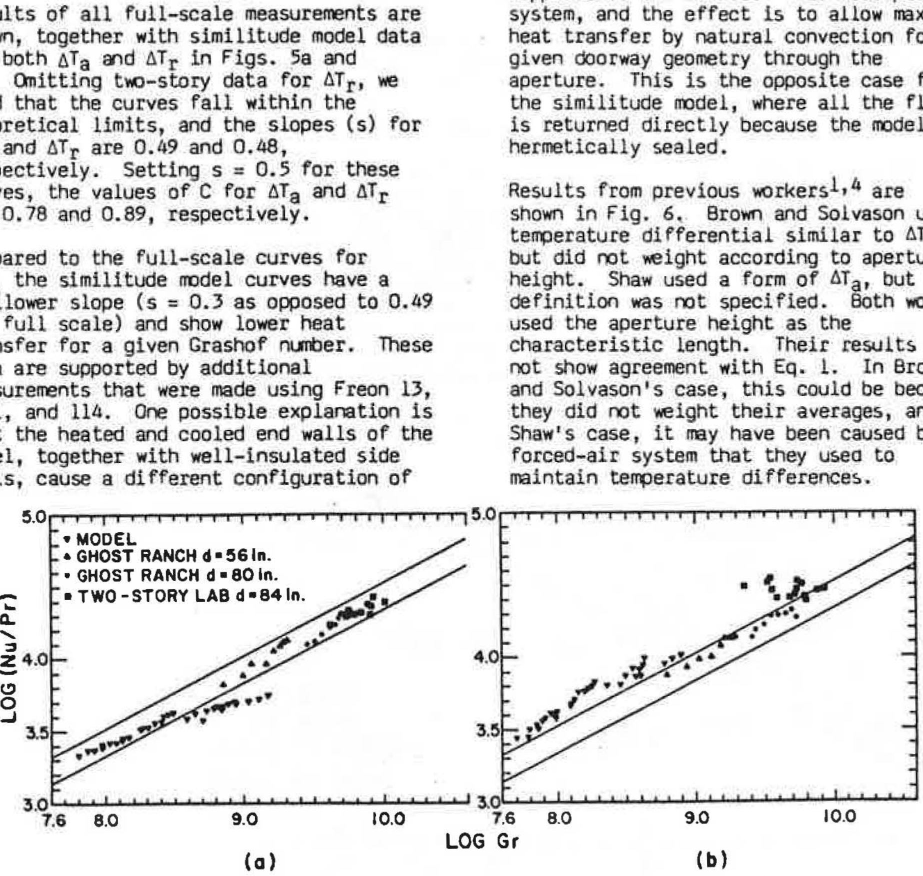

Fig. 5. Results of model and full-scale tests using ΔT_a in (a) and ΔT_r in (b). Upper and lower lines are the same as in Fig. 4.

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9. CONCLUSIONS

Results of similitude modeling show that characteristic length and characteristic temperature differentials can be found that allow an expression of the form of Eq. 1 that is independent of room and doorway geometries, and of the type of space heating. The doorway height, d, has been shown from both similitude modeling and Ghost Ranch tests to be a suitable characteristic length, and two temperature differentials, ΔT_a and ΔT_r, have been found suitable. The results for ΔT_a are consistent for full-scale tests involving three doorway heights in two buildings having completely different room geometries and different methods of heating. This temperature differential, ΔT_a, is, therefore, most suitable for monitoring heat flow through apertures in all geometries where temperature measurements can be made in the aperture. Using ΔT_a, Eqs. 1 and 2 become

$$\frac{Nu}{Pr} = 0.26Gr^{1/2}, \text{ and } \dot{q}_a = 4w(d\ \Delta T_a)^{3/2}.$$

In buildings where the rooms are normal-sized living spaces having low heat losses, ΔT_r could be used for prediction and building design, in which case Eqs. 1 and 2 become

$$\frac{Nu}{Pr} = 0.3Gr^{1/2}, \text{ and } \dot{q}_a = 4.6w(d\ \Delta T_r)^{3/2}.$$

For ΔT_r equal to 5°F, and for a typical doorway (d = 6.6 ft and w = 3 ft), $\dot{q}_a$ is 2600 Btu/h (760 W). Results from Eqs. 1 and 2 for ΔT_a and ΔT_r should be dependable to within ± 20%. It can be seen from these equations that doubling the doorway height will increase $\dot{q}_a$ by almost a factor of 3. A further study to relate ΔT_a and ΔT_r to building design parameters and thermal comfort would be useful.

10. ACKNOWLEDGEMENT

The authors wish to thank Donald A. Neeper for his continued support of this project and help in writing this paper, and to Jose Tafoya for his assistance in experimental work.

11. REFERENCES

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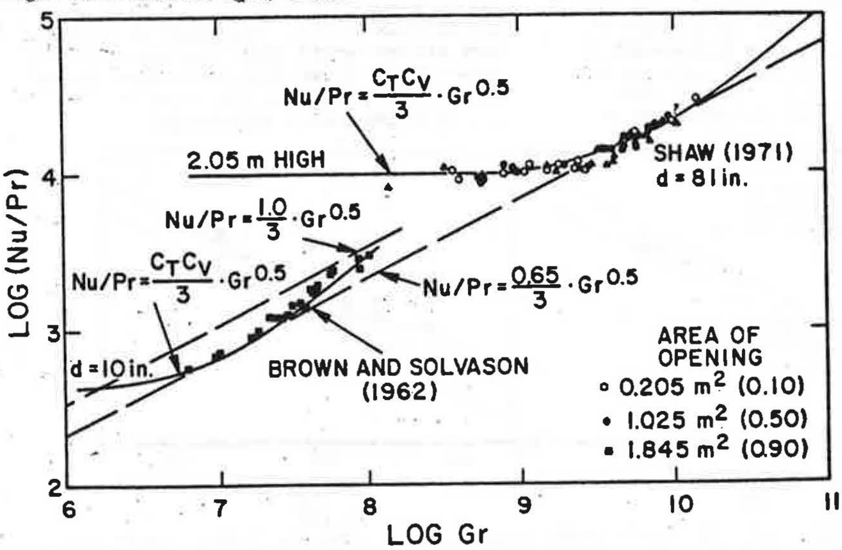

Fig. 6. Results from previous workers (after Shaw). An added factor, C_v, has been included to account for heat transfer caused by their test system.