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LASL SIMILARITY STUDIES: PART II

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SIMILITUDE MODELING OF INTERZONE HEAT TRANSFER BY NATURAL CONVECTION*

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ABSTRACT

A strict similitude study of natural convection heat transfer through an aperture between two rooms in a passively heated (Trombe wall) building is reported. Similitude numbers, experimental apparatus, and experimental technique are explained. Preliminary results are presented and discussed.

1. INTRODUCTION

Some historical and theoretical considerations for this natural convection study are presented in another paper of this conference, entitled "LASL Similarity Studies: Part I." The geometry and scaling parameters are suitable for the study of natural convection (NC) heat transfer from one room heated by a Trombe wall through a doorway to a thermal mass at a lower temperature in a second room. Although we address only this heating configuration, we expect that the heating geometry will not have a major effect on our results. We use similitude modeling to investigate this problem. The object is to determine a heat transfer coefficient, U_{12}, for interzone heat transfer through the aperture and to examine its functional dependence on geometric and dynamic factors.

2. SIMILARITY NUMBERS

Three similarity numbers, the Grashof (Gr), Prandtl (Pr), and the Nusselt (Nu) numbers are used in the study of NC heat transfer. (See Part I for definitions.)

When $Gr_m = Gr_p$ and $Pr_m = Pr_p$ (m and p refer to model and prototype, where the prototype is the full sized building to be studied), strict similitude is maintained in the fluid, i.e., velocity and temperature fields scale directly between model and prototype. Likewise, $Nu_m = Nu_p$ is used to scale U_{12}.

Selection of characteristic lengths (ℓ) and temperature differences (ΔT) in similitude modeling is not unique. Therefore, ℓ will be taken as the height (H) of the zone (see Fig. 1), and ΔT will be the difference in the average temperatures of the two zones for reasons given in Part I.

Numerous studies, both theoretical and experimental, have been made for the single cell case (sometimes called the window box).[1] A few[2,3] have addressed the problem of NC heat transfer through an aperture, but no case is known by the authors where a three-dimensional strict similitude model of a two-room passive building has been studied for NC heat transfer through an aperture.

3. SIMILITUDE MODEL

The prototype for this experiment could be a small two-room building with an eight-foot ceiling and each room would be 14 ft x 14 ft. The rooms would be separated by a partition with a door that will be movable and variable in height and width. The south facing room would be heated passively by a Trombe wall, and the northernmost wall of the north facing room would be massive for thermal storage. The model was geometrically scaled down by a factor of $H_p = 5.7\ H_m$, where p and m refer to prototype and model. To maintain strict similitude, Gr and Pr must be the same for both model and prototype. To maintain this equality, the temperature and kinematic viscosity of the model fluid must be adjusted to account for the factor of 185 which results from the H^3 factor in Gr. Since the Boussinesq approximation is made (that the fluid properties are constant

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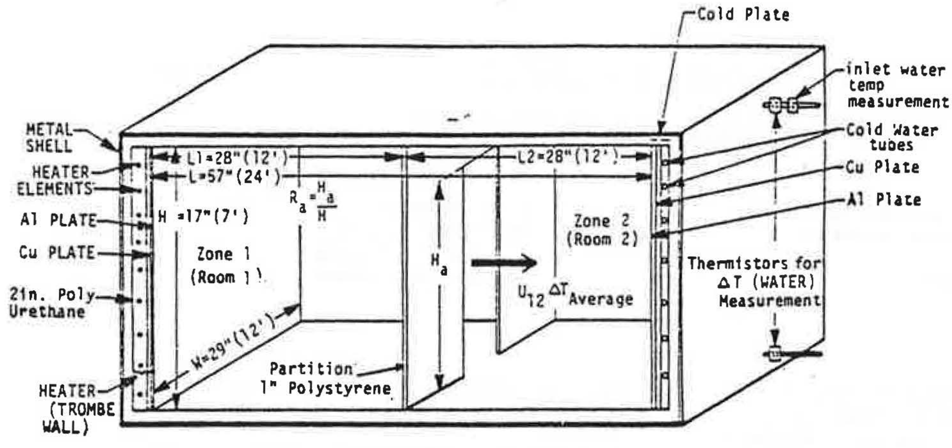

Fig. 1. Similitude Model (not to scale). Glass front and thermocouple racks not shown. Designations in parentheses for prototype.

over the range of temperatures used), most of the factor should come from Gr_m. Freon 114 has the desired characteristics, that is, $\nu_m^2 = 1/80\ \nu_p^2$, so that ΔT_m need only be about 2.3 ΔT_p to maintain the Grashof number constant. Furthermore, the Prandtl numbers of air and Freon 114 are the same so that strict similitude can be maintained within the model.

To check experimentally the similitude scaling, we can use Freon 12 by designing the experiment so that the Grashof number ranges for Freon 12 and Freon 114 overlap sufficiently. (Prandtl numbers for these two gasses differ by a factor of approximately 8/7.)

The shell of the gas-tight model is constructed of welded galvanized sheet metal, with a removable front cover (see Fig. 1). For visual observation, the front cover is a triple glazing. The remainder of the model is insulated on the inside with 2 in. of polyurethane insulation (R = 12) to minimize thermal losses.

To simulate a Trombe wall, an electric heater (referred to as the hot plate) was constructed from a sheet of copper, which is heated radiatively by a system of nichrome wires held about an inch behind the plate. To control vertical temperature differentials, the wires have three separate elements so that the power distribution can be varied as required. The nichrome wires are held taut by springs to account for thermal expansion. A sheet of aluminum was bonded to the copper (on the roomward side) in order to reduce radiative heat transfer through the aperture (emissivity of Al = .05) from the hot plate. The northern wall is simulated by another copper plate (referred to as the cold plate) with copper tubing soft soldered to the back and, again, bonded to a sheet of aluminum on the roomward side to reduce radiative heat transfer. A constant temperature bath circulates water through the tubing to maintain the cold plate at a constant temperature.

The partition separating the two cells is one-in. polystyrene and the aperture is simply cut from this partition.

Three-dimensional temperature fields are measured with a grid of 25 Type k thermocouples in each cell, mounted on a vertical rack which can be moved to scan most of the volume of the two cells. The thermocouples were calibrated in ice water (32°F) and are read and recorded on magnetic tape to 0.1°F accuracy with two Autodata Nine data acquisition systems. These data are used to generate three- and two-dimensional (3-D and 2-D) isotherm plots for determination of 3-D effects due to the aperture, asymmetry caused by the difference in conductivities between the glass front wall and the polyurethane back wall, and to determine temperature stratification, which is important for thermal comfort. The data are also used to calculate average cell temperatures and to calculate heat losses through the cell walls.

Temperatures are also measured at five positions each on the hot and cold plates to determine the vertical temperature variations. Ambient temperature, input water flow temperature, and 16 temperature measurements on the outside of the model are also recorded. The input water temperature is measured using a thermocouple, but the temperature difference between in-and-out flowing water is measured with two thermistors connected in a bridge circuit. The water flow is measured with a vibrating tube flowmeter.

4. EXPERIMENT AND ANALYSIS

The temperature difference (i.e., Gr) and the aperture aspect ratio R_a were varied to determine their effect on U_{12} through the aperture. Other geometric parameters were held constant.

The first experiment was performed with $R_a = .82$. Gr was varied in five increments by varying the power input which, in turn, determines ΔT. At each value of Gr, the temperatures, power input, water flow rate, and heat transferred to the cold plate were measured after the system reached the steady state. The time constant to reach steady state was six hours. Similar data were then taken for $R_a = 1.0$. From inside temperature fields, 2-D and 3-D isotherms were generated and average temperatures were calculated. From inside and outside wall temperatures, heat losses through the outer shell of the model were calculated. Heat into the hot plate and out of the cold plate are also determined. Data were obtained with Freon 12 and Freon 114.

5. RESULTS AND DISCUSSION

In Fig. 2 the Nusselt number is plotted for the two values of R_a as a function of Gr. The curves have the form

$$Nu = K(R_a)\ Gr^b$$

In order to see what these curves mean with respect to the prototype, U_{12} as a function of $\Delta\bar{T}$ is also shown. Here the prototype corresponds to an 8 ft ceiling ($H_p = 5.65\ H_m$) and can be directly compared with the example presented in Part I.

Figure 3 shows the 3-D 98°F isotherm for $R_a = .82$ for both the hot and cold cells. Asymmetry caused by the differences in conductances of the glass front and back walls are seen to be negligible. Especially interesting is the distortion caused by the aperture. This distortion is mostly confined to the width of the aperture, strongly indicating that the dependence of U_{12} on aperture location is negligible.

In this experiment it was attempted to maintain strict similitude by keeping both Gr and Pr constant for both model and prototype. There are, however, several factors which are not similar in the model. These are: (1) the aluminum surfaces on the hot and cold plates make radiative heat transfer negligible in the model, (2) edge effects due to insulation thickness, and (3) possible disturbances in the cells due to the measurement apparatus. These factors should have a relatively minor influence on U_{12}.

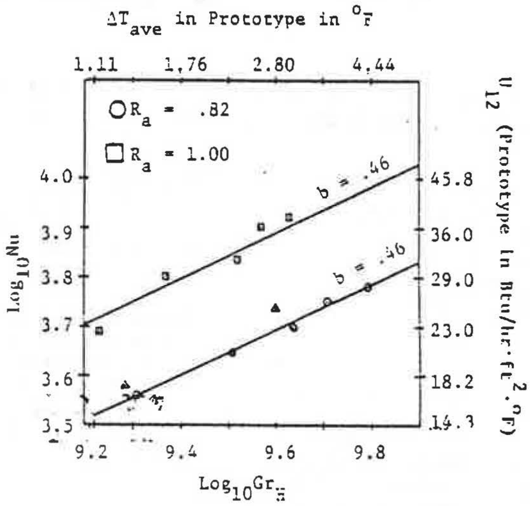

Fig. 2. Plots of Log Nu (U_{12}) vs Log Gr (ΔT) for two values of aperture aspect ratio R_a. Points (▲) are data for Freon 12 with $R_a = .82$. All others are for Freon 114.

We expect dependence of U_{12} upon R_a to be much more pronounced than its dependence on the aperture width. Strong temperature gradients exist vertically while almost none exist horizontally. When R_a is less than unity, hot fluid is trapped in the volume above the aperture, which inhibits convection since the hot fluid must be driven downward to pass through the aperture. Hence, we have changed R_a while keeping the aperture area constant. This necessitated making the aperture narrower. However, as indicated by our example in Part I, we do not expect U_{12} to be very sensitive to the ratio of aperture width to cell width over the normal range of doorway dimensions.

The preliminary results of Fig. 2 show good overlap in our data for Freon 12 and Freon 114. (Only the two points of Freon 12 which overlap the range of Freon 114 Grashof numbers are shown.)

6. CONCLUSIONS

Two variables which affect the natural convection heat transfer coefficient U_{12}

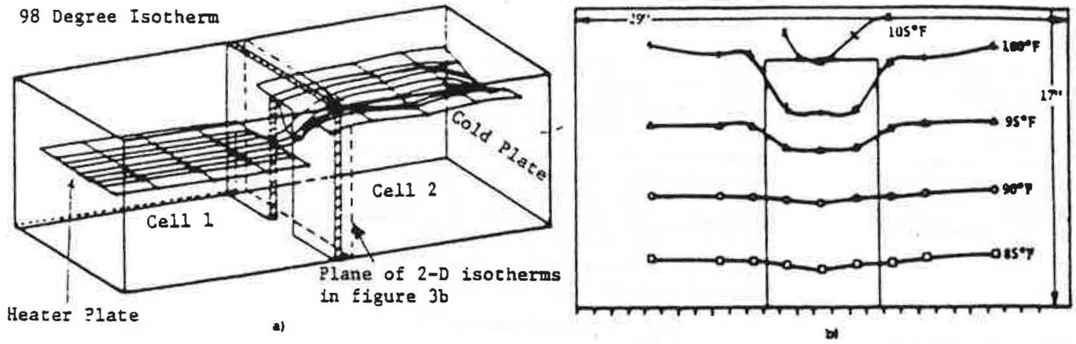

Fig. 3. a) Three-dimensional 98°F isotherm for Gr equal to 4.5×10^9 and R_a = .82. b) Two-dimensional isotherms for some Gr and R_a as in a) in the plane (shown in a) parallel to the aperture.

are examined in this paper. They are Gr and R_a. All relationships are expressed in non-dimensional form to permit direct scaling to the real world. The Nusselt number is expressed in terms of Gr and R_a and was found to be of the form

$$Nu = K(R_a)\ Gr^b;$$

with b approximately .46 (the value of .46 for R_a = 1.0 was obtained neglecting the point at Log Gr = 9.23 since experimental difficulties with Freon leakage developed during this set of measurements), which is close to the value of .50 predicted by Brown and Solvason.[2] The data in Fig. 2 give $K(R_a = .82) = 1.9$ and $K(R_a - 1.0) = 2.9$.

The functional dependence of U_{12} on R_a is not determined since only two values were measured. However, Fig. 2 shows a substantial increase in Nu when R_a is increased from .82 to 1.00. The overlap of data points in Fig. 2 for Freon 12 and Freon 114 give confidence that our results can be reliably scaled to a full-sized structure (the prototype). In order to compare results for the two gasses we had to account for the linear variation of Nusselt number with Prandtl number as discussed in Part I. Hence, the Freon 12 data points shown are equal to 7/8 Nu, the factor 7/8 being the ratio of the corresponding Prandtl numbers.

The absolute value of our coefficients U_{12} may have a relatively large error; however, we expect their relative magnitudes and functional dependence upon Gr to be well described by the curves shown.

From qualitative evaluations of 3-D isotherms, it is seen that the horizontal location of the aperture has, at most, a weak influence if it is located at one of the side walls.

Future experiments will be aimed at determining the functional dependence of all relevant variables. It is hoped that this work will aid architects and engineers in designing passive solar buildings for more effective use of natural convection currents.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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