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# SCALE MODEL SIMULATION OF BUILDING AIR FLOW: COMPARISON WITH CSU REPEAT FACILITY

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ABSTRACT

The results of a scale model study of natural convection flows in the CSU REPEAT facility are reported. The scale experiments were designed to model natural convection flows for summer conditions when heating and cooling are limited primarily to the sunspace and clerestory glass of full-scale facility. Flow visualization studies and velocity measurements from the scale experiment are compared to velocity measurements taken in the building. The scale experiment was successful in modelling changes in flow patterns that occur in the CSU REPEAT facility throughout the day. The thermal boundary condition on the upper north wall of the scale experiment was found to play an important role in determining the overall structure of the natural convection flow.

## 1. INTRODUCTION

The performance of passive solar buildings depends directly on the ability to transport heated and cooled air throughout a building in an efficient manner. Natural convection air flow determines the performance of passive solar buildings in three ways. Air flow is responsible for: the energy removal from the surfaces that absorb solar energy; the energy transport between building zones; and the energy delivery to convectively coupled thermal storage.

At this time, we are unable to predict the magnitude or direction of the air flow in complicated building geometries. There are two major approaches to experimental research in this area:

- Full-scale experiments
- Small laboratory-scale experiments.

Measurements in full-scale buildings must be made to determine the geometries and thermal boundary conditions that are important in the real world, but small-scale experiments offer a number of advantages, including exact control of thermal boundary conditions, and ease of modification. The primary objective of this study is to verify that a water-filled scale test cell can be used to simulate the behavior of the full-scale reconfigurable passive test (REPEAT) facility at Colorado State University (CSU). The use of scale model experiments is based on the principle of dynamic similarity, first established by Osborne Reynolds in 1883 (1). If the scale experiment is geometrically similar to the full-scale problem, and the forces acting on a fluid parcel in the scale experiment have the same ratio as they do in the full-scale problem, then the results of scale experiment can be extrapolated to predict results in the full-scale problem.

The similarity of the scale experiment to the full-scale problem is guaranteed by matching the important nondimensional parameters that result from the geometry of the problem and the governing equations for conservation of mass, momentum, and energy. For the case of natural convection air flow in the CSU REPEAT facility during summertime conditions, the important nondimensional parameters are the Rayleigh number, the Prandtl number, the aspect ratios of the rooms and sunspace, and the parameter $\theta_{tc}$, which describes the temperature distribution on the north wall of the REPEAT facility. The choice of $\theta_{tc}$ is based on the observation that the thermal boundary conditions on the north wall and sunspace glass appear to determine the air flow patterns in the REPEAT facility throughout a large portion of the day under summertime conditions.

## 2. EXPERIMENTS

The validation experiments were performed in a 0.3048-m cubical water-filled test cell. A plexiglas partition was installed in the test cell to divide it into three zones, which correspond to the sunspace, upper north, and lower north rooms of the REPEAT facility. The dimensions of these zones are shown in Figure 1 for the SERI test cell and Figure 2 for the REPEAT facility test cell. Heating and cooling in the water-filled test cell were accomplished by pumping hot water

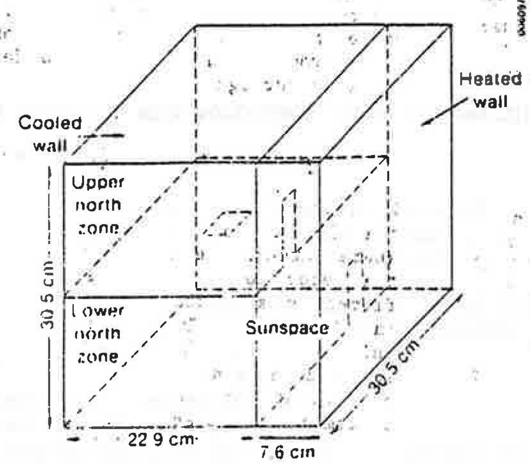



**Fig. 1. Dimensions of the SERI test cell.**

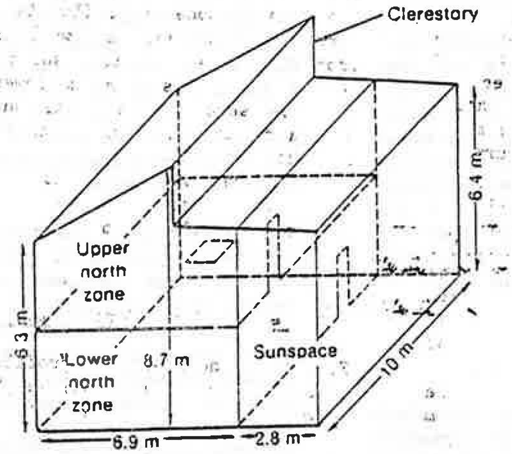



**Fig. 2. Dimensions of the REPEAT facility at Colorado State University.**

through the outer wall of the sunspace to simulate a window heated by absorption of diffuse radiation, and pumping cold water through the outer wall of the north rooms to simulate the presence of cold thermal storage. The thermal boundary condition on the outer wall of the upper north zone was varied during the experiment to match temperature changes that were measured in the REPEAT facility.

Water, rather than air, was used as the heat transfer fluid in the SERI test cell because it allows one to reach the high Rayleigh numbers characteristic of full-scale building, in a small apparatus. During the tests described in the present study, the SERI test cell was operated at a Rayleigh number of approximately 1.6E10. The Rayleigh number in the REPEAT facility tests was approximately 5.3E11. Both Rayleigh numbers are within the upper limits of the laminar boundary layer regime, characterized by the formation of thin boundary layers on the heated and cooled vertical walls (4,5). Water has a higher Prandtl number than air, but this has only a minor effect on the heat transfer. Established correlations can be used to compensate for this effect (5,6).

Type-T thermocouples were imbedded in the cooled and heated plates of the test cell at three locations: the center of the heated plate ($T_h$), along the centerline of the cooled plate, 7.6 cm ($T_{bc}$), and 15.2 cm ($T_{mc}$) from the bottom. Another thermocouple was taped to the inner surface of the upper north wall ($T_{tc}$). Temperatures in the test cell were measured using a thermocouple that could be moved up and down on a traverse.

Since two of the walls and the ceiling of the test cell were made of plexiglas, both quantitative and qualitative studies of the flow were possible. Two flow-visualization techniques were used. To show the direction of the flow between zones, dye was injected through a needle mounted on a traverse. To give an idea of the relative speeds in the doorways, the water was seeded with highly reflective neutrally buoyant particles, and a cross section at the inside and outside of each doorway was illuminated with a sheet of laser light. Particles in the lighted region showed up as streaks in timed-exposure photographs. Finally, velocities in the upper and lower doorways were measured using a laser-doppler velocimeter (LDV).

The results from the SERI test cell were compared to data from the REPEAT facility at CSU, as reported by (2,3). The REPEAT facility is a full-scale building, heated by solar energy entering through the sunspace and clerestory glass. Only summertime data were used in the comparison, since the SERI test cell models are heated by diffuse radiation.

Thermocouples and a hot-wire anemometer were used in the CSU REPEAT facility to measure detailed temperature and velocity profiles in the doorways. Some additional temperatures were measured at the walls and in the three zones. Velocity measurements were supplemented by smoke flow visualization to determine the direction of the flow in the doorways. Measurements were taken every hour for several days in May, July, October, and November of 1984.

One of the most interesting features of the REPEAT facility is the nonuniformity of the thermal mass on the north wall. The lower north wall consists of 25-cm thick concrete, while the upper north wall is constructed of gypsum wall board. Since the wall board has very little thermal mass compared to the concrete wall, the north wall temperatures in the upper and lower north zones tend to decouple thermally. The lower north wall remains at a fairly constant low temperature throughout the day, while the temperature of the upper wall changes. The upper north wall is sometimes as much as 10°C hotter than the lower north wall. The SERI test cell use electric heating to model the heating of the upper north wall of the building by diffuse radiation through the clerestory.

## 3. RESULTS

Three sets of experiments were performed in the SERI test cell to model temperature variations seen throughout the day in the REPEAT facility. Experiments were performed with:

- An approximately isothermal north wall
- Styrofoam insulation 1 cm thick, installed along the upper north wall
- Electric heating of the upper north wall.

The thermal boundary conditions created by these modifications can be succinctly described by defining the parameter $\theta_{tc}$ as,

$$\theta_{tc} = (T_{tc} - T_{bc})/(T_h - T_{bc}) .$$

This parameter represents the extent to which the upper north wall participates in cooling or heating air from the sunspace. When the upper north zone is not insulated, the entire north wall is cold, and $\theta_{tc}$ is close to zero. Under these conditions, cooling occurs in both the upper and lower north zones. With the insulation in place, the temperature of the upper north wall rises, and $\theta_{tc}$ rises to around 0.9. This increase makes the upper north wall less important in cooling the heated air from the sunspace. The temperature of the upper north wall can be raised further by electric heating, giving values of $\theta_{tc}$ above one. For values of $\theta_{tc}$ larger than one, the upper north zone is hotter than the sunspace glass and begins to heat air from the sunspace.

Three dimensional flow patterns were observed for all thermal boundary conditions tested. Horizontal velocity profiles were measured at several heights near the lower door, the results are presented in Figure 3. Since the LDV measuring volume could not be placed in the doorway itself, the measurements were taken approximately five millimeters into the sunspace (a) and into the lower north zone (b). The LDV was oriented so that only the north-south component of velocity was measured. This component was found to be much stronger on the downstream side of the doorway than on the upstream side. This apparently indicates that the water funnels into the doorway from many directions, and is directed outwards more uniformly when it leaves the doorway. Also, there is a strong and sometimes asymmetrical variation in velocity in the east-west direction across the doorway. These results demonstrate that doorway velocity profiles must include horizontal as well as vertical traverses if they are to be used to perform an energy or mass balance. However, the vertical profile measured at any horizontal position across the doorway has the same general shape, and can be used for qualitative comparisons. The three thermal boundary conditions of the test cell produced dramatically different flow patterns through the doorways.

### 3.1 Isothermal North Wall, $\theta_{tc}$=0

When the north wall was isothermal ($\theta_{tc}$=0), the flow was observed to travel into the sunspace through the lower door and out through the upper door. This observation was confirmed by a vertical LDV profile, presented in Figure 4a. This figure, which presents only the velocity component in the north-south direction, shows that velocities are highest at the top of the upper door and the bottom of the lower door.

### 3.2 Insulated Upper North Wall, $\theta_{tc}$=0.9

The flow pattern becomes much more complicated when insulation is installed in the upper north zone. The flow is no longer unidirectional in each doorway, as can be seen from Figure 4b, which shows the doorway velocity profiles. In the lower doorway, the flow is strongly into the sunspace at the bottom of the door, and into the lower north zone at the top. In the upper door the flow is into the upper north zone at the top and bottom of the door. In the middle, there is a weak reverse flow into the sunspace.

### 3.3 Heated Upper North Wall, $\theta_{tc}$=1.4

Figure 4c shows the LDV profiles for the case when the upper north wall was heated to simulate the heating through the clerestory. The flow in this case is also fairly complicated. As in the other two configurations there is a strong flow into the sunspace at the bottom of the lower door. In addition, since the upper north wall is hotter than the sunspace glass, water travels into the sunspace at the top of the upper doorway. At the bottom of the upper doorway and the top of the lower doorway, the flow is out of the sunspace. The velocity measurements are confirmed by streak photographs, such as Figure 5, which shows the flow through the upper door. The illuminated section is a few centimeters wide in the north-south direction, and a few millimeters wide in the east-west direction. Motion in the east-west direction is not recorded on the photographs, since particles travelling in that direction quickly move out of the illuminated region. Note, the shear region between the upper part of the door where the flow is into the sunspace and the lower part, is into the upper north zone. Dye injection photographs, such as Figure 6, confirm the observed flow directions in the lower door.

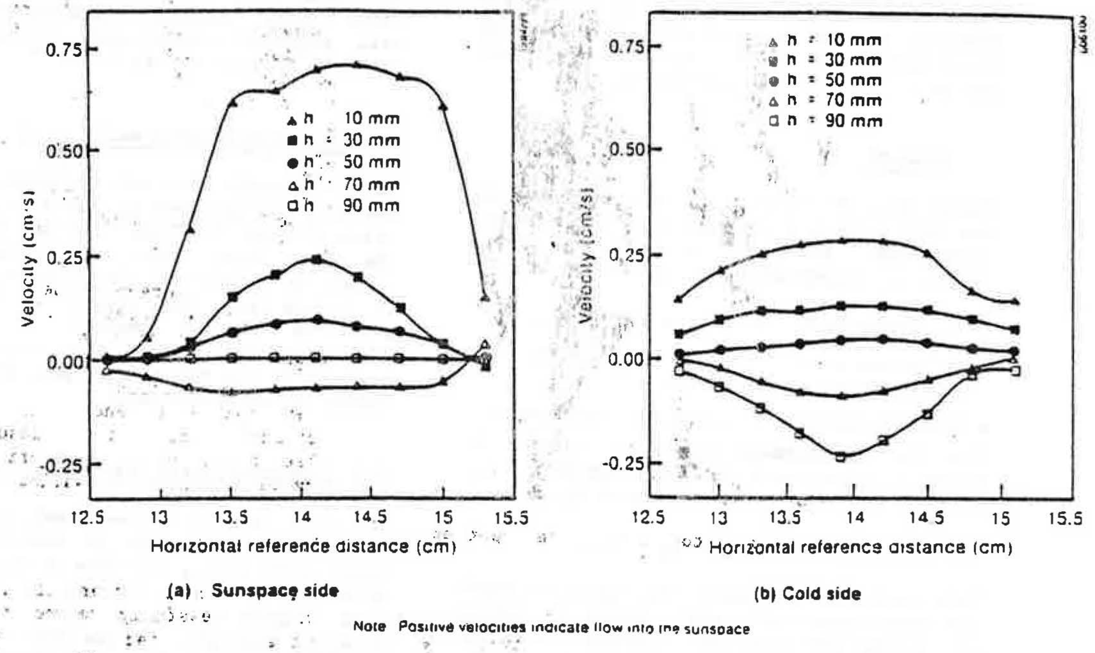



**Fig. 3. Horizontal velocity profiles of the SERI test cell.**

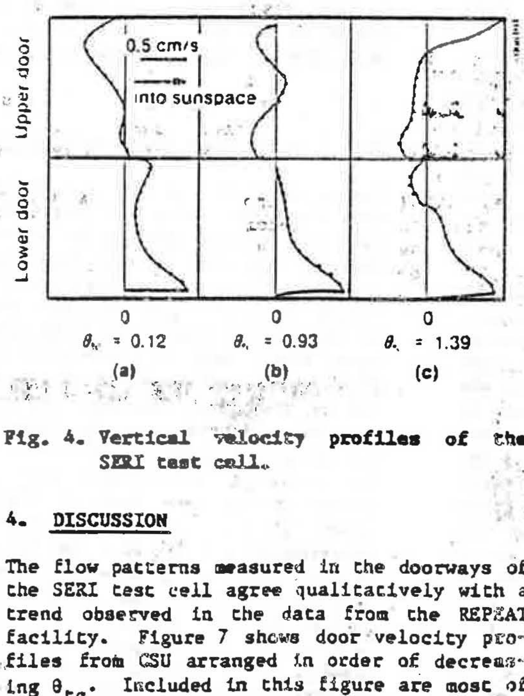



**Fig. 4. Vertical velocity profiles of the SERI test cell.**

## 4. DISCUSSION

The flow patterns measured in the doorways of the SERI test cell agree qualitatively with a trend observed in the data from the REPEAT facility. Figure 7 shows door velocity profiles from CSU arranged in order of decreasing $\theta_{tc}$. Included in this figure are most of the available data from May and July. We omitted cases where the inner wall of the sunspace was hotter than the outer wall, which could not be modelled with our apparatus as presently configured.

Several interesting trends can be observed from the sequence of velocity profiles measured in the CSU REPEAT facility. First, it is apparent that the flow rate in each direction (proportional to the area of the profile, bounded by the zero velocity line) increases as $\theta_{tc}$ decreases. This makes sense because heat transfer in the upper north zone is increasing as $\theta_{tc}$ decreases. Secondly, the shape of the velocity profiles changes. At the highest value of the $\theta_{tc}$, 1.41, the flow goes into the sunspace at the top of the upper and bottom of the lower doorway, and into the north zones at the bottom of the upper and top of the lower doorway. In the middle of each doorway, there is a region of zero velocity. As $\theta_{tc}$ decreases, the flow in the lower doorway maintains the same general shape, but the outward flow through the lower part of the doorway becomes stronger and extends higher than before. In general, the region of flow into the lower north zone becomes less and less important as $\theta_{tc}$ decreases. In the upper doorway, the flow is unidirectional (into the upper north zone) when $\theta_{tc}$ is less than one. The shape of the profile changes as $\theta_{tc}$ decreases, gradually changing from a profile with two peaks of approximately equal size at the top and bottom, to one in which the velocity decreases almost monotonically from a maximum at the top of the doorway.

The SERI velocity profiles for the heated, insulated, and isothermal cases were measured with $\theta_{tc}$ =1.39, 0.93, and 0.12 respectively. Thus, the insulated and heated cases fall within the range covered by the REPEAT data, while the isothermal case has $\theta_{tc}$ lower than the lowest available CSU data.

The value of $\theta_{tc}$ for the heated case is very close to that of the first profile from the

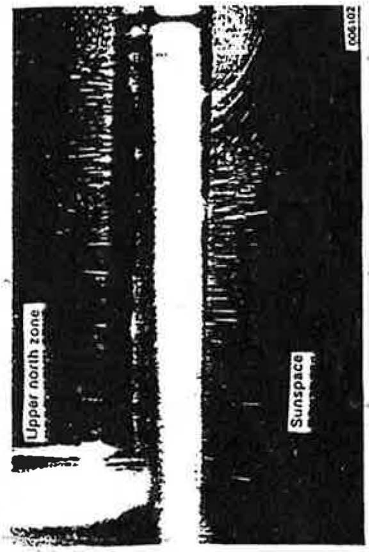



**Fig. 5. Streak photograph of the upper door, $\theta_{tc} = 1.4$**

REPEAT facility (7:30 P.M. in May), and the two flow patterns are qualitatively very similar. In both cases, there is bidirectional flow in each doorway. A comparison of Figures 4 and 7 shows that the flow directions are the same.

The data for the insulated case at SERI should be compared with the third profile of Figure 7 (4:30 P.M. in May). The overall features of the flow are consistent with the trends in the REPEAT data. The upper door has strong peaks of flow from the sunspace at the top and bottom; the lower door has strong flow into the sunspace at the bottom and lower reversed velocities at the top. The only significant difference is the SERI profile has a region of low-velocity reverse flow at the center of the upper door.

The SERI test cell without insulation has a low value of $\theta_{tc}$, generally well below 0.2. This is lower than the available REPEAT data. However, the tracer particle photographs are consistent with REPEAT data with the lowest positive value of $\theta_{tc}$ (0.49). The flow was observed to be unidirectional in each doorway, and in the direction indicated in the REPEAT data. Maximal velocities occur near the bottom of the lower door and the top of the upper door. Furthermore, the maximum velocities are somewhat greater than those in the insulated case.

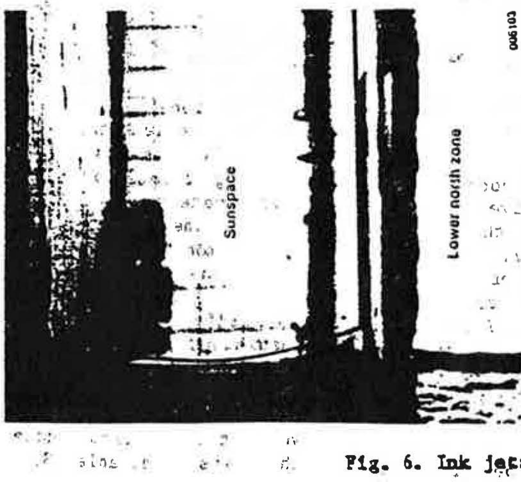
Qualitative agreement between CSU and SERI data has been observed for the velocity profiles in both doorways. This agreement confirms that it is appropriate to characterize natural-convection flow patterns in a complex, multi-zone enclosure by thermal boundary conditions of the enclosure, and suggests that the air movement is driven by the boundary layers along the walls.

## 5. CONCLUSIONS

Using a small, water-filled scale model, we have successfully reproduced the main flow patterns reported for diffuse sunlight conditions in the CSU REPEAT facility (2). We produced these flow patterns by varying the thermal boundary conditions of the test cell, as described by the parameter $\theta_{tc}$.

Our ability to predict the direction of air flows in a building, given its geometry and thermal boundary conditions, suggests that small-scale modelling may be useful as a tool for designers of passive solar buildings.

The importance of the boundary conditions in determining the flow patterns implies that further research in full-scale buildings should emphasize wall temperature measurements in addition to measuring room temperature distributions.



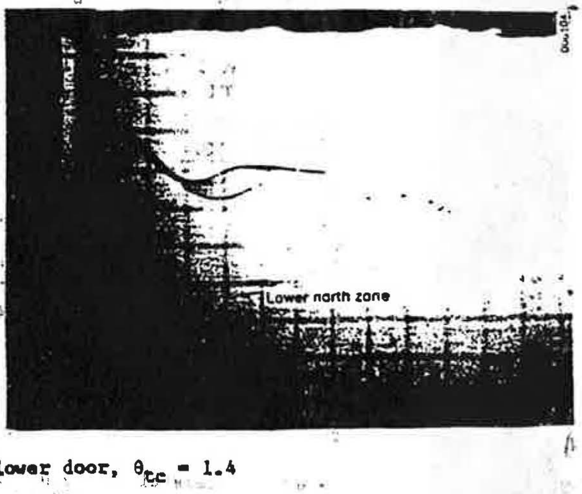




**Fig. 6. Ink jets, lower door, $\theta_{tc} = 1.4$**

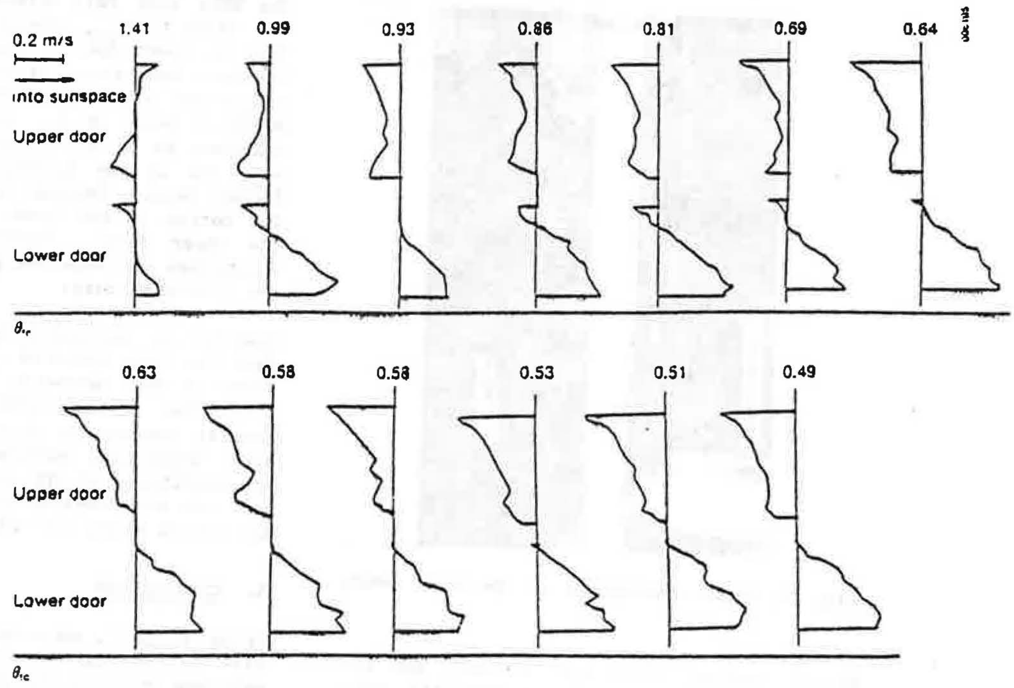



**Fig. 7. Door velocity profiles from the REPEAT facility.**

## 6. REFERENCES


(1) Schlichting, H., 1979, Boundary Layer Theory, McGraw-Hill, New York, p. 12.

(2) Kirkpatrick, Allan, Dallas Hill, and Kirk Stokes, 1984, "Natural Convection Flow Profiles in a Passive Solar Building," presented at the 1984 ASES Passive Solar Conference.

(3) Kirkpatrick, Allan, May, 1985, Private communication.

(4) Bohn, M. S., D. A. Olson, and A. T. Kirkpatrick, 1983, "Experimental Study of Three Dimensional Natural Convection at High Rayleigh Number," J. of Heat Transfer, Vol. 106, pp. 339-345.

(5) Churchill, S. W., 1983, "Free Convection in Layers and Enclosures," from Heat Exchanger Design Handbook, ed. by E. U. Schlunder, Hemisphere Publishing, Washington, D.C.

(6) Bohn, Mark S., and Ren Anderson, 1984, "Influence of Prandtl Number on Natural Convection Heat Transfer Correlations," SERI/TR-252-2067, Solar Energy Research Institute, Golden, CO.