variations in flow coeff. related to various temperature distributions

20 apertures
C mass flow coeff Eq 4
Cq heat 7
10

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FLOW COEFFICIENTS FOR INTERZONAL NATURAL CONVECTION FOR VARIOUS APERTURES

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ABSTRACT

Experiments to determine the flow coefficients for interzonal natural convection were carried out at the National Bureau of Standards' Passive Solar Test Facility. Interzonal natural convection was studied for ten different apertures under four different test conditions. One of the two zones was heated with baseboard electric heaters. The flow coefficients used in simple one-dimensional model for interzonal airflow vary with the aperture configuration, ratio of aperture area to wall area, and the level of heat input to the warmer zone. Variations in the flow coefficients are apparently due to the different flow fields and temperature distributions for each aperture configuration.

NOMENCLATURE

- A_a = Aperture cross section area (m^2)
- A_w = Cross section area of the wall containing the aperture (m^2)
- $A^* = A_a/A_w$ = Aperture area to wall area ratio (non-dimensional)
- C = Discharge coefficient or aperture mass flow coefficient (non-dimensional)
- C_p = Specific heat or air (J/kg °K)
- C_q = Aperture heat flow coefficient (non-dimensional)
- C_t = Temperature correction coefficient (non-dimensional)
- g = Acceleration due to gravity (m/s^2)
- H = Height of the aperture. (m)
- L = Vertical distance from center of wall to the bottom of the split window, defined in figure 3 (m)
- M = Mass flow rate (kg/s)
- M_r = Reference value of mass flow rate (kg/s)
- Q = Heat flow rate (W)
- Q_r = Reference value of heat flow rate (W)
- T_1 = Average value of temperature in zone 1 (°C or °K)
- T_2 = Average value of temperature in zone 2 (°C or °K)
- $\bar{T}$ = $(T_1 + T_2)/2$ (°K)
- T_r = Reference value of $\bar{T}$ (°K)
- ΔT = $(T_1 - T_2)$, zone-to-zone temperature difference (°K)
- ΔT_r = Reference value of zone-to-zone temperature difference (°K)
- U = Air velocity in the aperture (m/s)
- U_m = Maximum possible air velocity (m/s)
- W = Width of the aperture (m)
- Y = Vertical distance from the mid-height of the aperture (m) (Figure 3)
- Y_m = H/2 (m)
- ρ = Density of air at a temperature equal to $\bar{T}$ (kg/m^3)

Subscript

- 1 = zone 1, warmer of the two zones
- 2 = zone 2, cooler of the two zones
- m = maximum value
- r = reference value

Superscript

- * = non-dimensionalized quantity

INTRODUCTION

Interzonal natural convection plays a major role in the distribution of heat in passive solar buildings. Thermal performance and comfort in passive solar buildings can be improved if apertures are properly configured or designed for effective interzonal convective heat transfer. The design process needs methods for predicting the interzonal natural convective heat transfer through different aperture configurations.

Recent experimental studies [1-3] conducted at the National Bureau of Standards (NBS), showed that the interzonal natural convective airflow through a doorway is three-dimensional and that the temperature distribution within each zone significantly affects the interzonal natural convection. It was also shown that the existing one-dimensional models [4-10] for predicting interzonal natural convection cannot properly account for the three-dimensional aspects of the flow and temperature field and the losses due to viscosity at the aperture boundaries. However, the use of flow coefficients (a discharge coefficient for velocity and mass transfer, and a temperature correction coefficient for heat flow) in one-dimensional models make it possible to bring the predicted and measured values within reasonable agreement. Results of these studies suggest that the one-dimensional model can adequately predict the interzonal natural convective heat and mass transfer for any aperture provided that the proper values of the flow coefficients are used in the one-dimensional model.

The NBS studies found that for a doorway the value of discharge coefficient, C, to be used in the one-dimensional model varied between 0.45 and 0.54. These values are 11 to 26% lower than the commonly recommended value of 0.61 [4-6]; and 20 to 34% lower than a value of 0.68 given in reference 10. This difference in discharge coefficient values appears to be due to the difference in experimental set-ups and aperture configurations. To better characterize the important flow coefficients, interzonal natural convection was experimentally studied for various aperture configurations under different test conditions. Experiments were conducted for ten aperture configurations for a two-zone set-up with four different levels of heat input to the warmer of the two zones. This paper will briefly describe the aperture configurations and the measurement procedure, and present representative results.

SIMPLE MODEL

The one-dimensional model presented below follows the theory developed in reference 4. Assuming that the zone-to-zone temperature difference is independent of vertical distance, Y, the magnitude, U, of the instantaneous local air velocity along a streamline in the aperture may be expressed as:

$$U = C\,(2gY\Delta T/\bar{T})^{0.5} \qquad (1)$$

Equation (1) may be rewritten in non-dimensional form as:

$$U^* = U/U_m = C(Y^*)^{0.5} \qquad (2)$$

$$U_m = (2gY_m\Delta T/\bar{T})^{0.5} \qquad (3)$$

Where U_m is the maximum possible velocity for a given value of Y_m, ΔT and $\bar{T}$. The coefficient C, is an aperture mass flow coefficient (or discharge coefficient) which accounts for the viscous losses at the aperture boundaries. The interzonal mass flow rate, M, is obtained by integration of the local velocity between Y = 0 and $Y = Y_m$, and may be expressed as:

$$M = C(2/3)(\rho W Y_m^{1.5})(2g\Delta T/\bar{T})^{0.5} \qquad (4)$$

Equation (4) gives mass flow rate for both the outflow (i.e., the flow of warm air to the cooler zone) and the inflow (i.e., the flow of cool air to the warmer zone). Equation (4) may be written in non-dimensional form as:

$$M^* = M/M_r = C\,(\Delta T^*/T^*)^{0.5} \qquad (5)$$

$$M_r = (2/3)(\rho W Y_m^{1.5})(2g\Delta T_r/\bar{T}_r)^{0.5} \qquad (6)$$

Where, M_r is the reference value of mass flow rate for a given aperture configuration (i.e., W and Y_m) computed for a reference value of zone-to-zone temperature difference, ΔT_r, and reference average temperature, $\bar{T}_r$. For the purpose of this study, we assume that ΔT_r = 1°K, and $\bar{T}_r$ = 295°K (a value very close to the actual value of $\bar{T}$ for the experiments described in this paper).

The associated heat transfer rate through the aperture may be expressed as:

$$Q = C_t\, C_p M \Delta T \qquad (7)$$

Equation (7) may be written in non-dimensional form as:

$$Q^* = Q/Q_r = C_q\,(\Delta T^3/T^*)^{0.5} \qquad (8)$$

$$Q_r = C_p M_r \Delta T_r \qquad (9)$$

$$C_q = C\,C_t \qquad (10)$$

Where, Q_r is the reference value of the heat transfer rate for a given aperture. The quantity C_q is an aperture heat flow coefficient. The quantity C_t is a temperature correction coefficient; it accounts for the difference in the value of average air temperature based on the zone temperatures and the temperature of air moving through the aperture. A quantity similar to C_t has been used by other researchers [6].

Earlier results [1-3,6,8-11) suggest that the simple one-dimensional model discussed above may adequately predict the interzonal natural convection for any aperture configuration for a two zone set-up if the proper values of the flow coefficients (C, C_t, and C_q) are used in the respective equations.

DESCRIPTION OF THE EXPERIMENTS

Full scale natural convection experiments were conducted at the NBS Passive Solar Test Facility. A floor plan of the building is shown in figure 1. Direct solar radiation was blocked from entering the cell #3, and the cell was divided into two zones. Figure 2 shows the locations of the three baseboard heaters and the strings of nine thermocouples used to monitor the temperatures in each zone. The wall separating the two zone, i.e., the common wall, was constructed of 5.1 cm (2 in.) thick extruded polystyrene which easily enabled the construction of different aperture configurations.

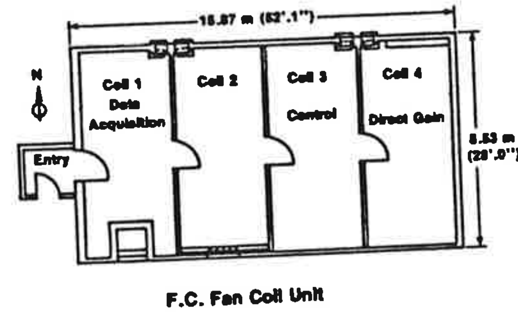

Fig. 1 Floor plan of the NBS Passive Soalr Test Building

The ten aperture configurations used in these experiments are summarized in Table 1, and are shown schematically in figures 3 and 4. These include: (1) a split window, i.e., two small windows situated symmetrically about the horizontal bisector of the

Table 1. Summary of Tests Conducted for Various Apertures

Number	Description	Height (m)	Width (m)	Aa/Aw	0	500W H_2	1,000W H_1,H_3	1,500W H_1,H_2,H_3
	APERTURE				TEST CONDITIONS Heat input into zone #1 during the test, and heater location			
1	split-window upper	.46						
	lower	.46	.686	.067[1]	x	x	x	x
2	window	1.07	.686	.080	x	x	x	x
3	side-door	2.00	.686	.150	x	x	x	x
4	(4-8) center-	2.00	.508	.111	x	x	x	x
5	doors normal	2.00	.686	.150	x	x	x	x
6	configuration	2.00	.914	.200	x	x	x	x
7		2.00	1.22	.267	x	x	x	x
8		2.00	1.33	.300	x			x
9	(9,10) center-	2.00	.686	.150	x	x	x	x
10	doors step-up	2.00	.914	.267	x	x	x	x

1 Both the upper and lower (figure 3) window are considered an aperture for computing area ration Aa/Aw.

common wall; (2) a normal window; (3) a side door, i.e., a door situated away from the middle and adjacent to a corner; and (4-8) center doors of five different widths; and (9-10) center doors of two different widths in a step-up configuration. For the step-up configuration, shown in figure 4, the floor of the cooler zone is about 0.25 m higher than the floor of the other zone. Experiments for each aperture were conducted with four different levels of heat input to Zone #1 as shown in Table 1. Aperture number 8 was an exception. For this aperture, tests were conducted under only two conditions and no data were collected because flow velocities were too small to measure.

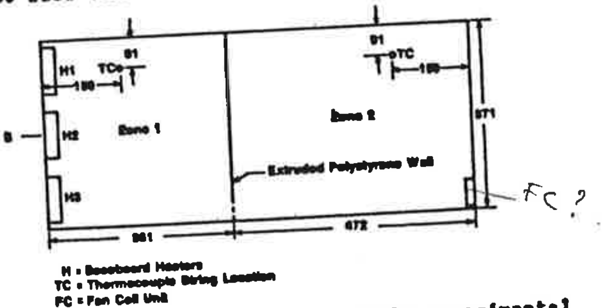

Fig. 2 Schematic floor plan of the experimental area

Before starting an experiment, the aperture was blocked with a removable extruded polystyrene panel. Zone #1 was heated by the electric baseboard heaters, while zone #2 was cooled using a fan coil cooling unit. When the average zone-to-zone temperature difference was greater than 10°C, the auxiliary cooling in zone #2 was turned off and the panel blocking the aperture was removed to start the experiment. The status of the (i.e., warmer of the two zones) heat input to zone #1 for different experiments has been summarized in Table 1. Data were then collected every two minutes for a period of three hours.

The velocity and temperature distributions of the airflow through the aperture were measured with six hot wire anemometers and six thermocouples located along the vertical centerline of the aperture. Temperatures were measured with type-T thermocouples. The maximum uncertainty is estimated to be 0.5°C in the temperature measurements and 0.025 m/s in the air speed measurements.

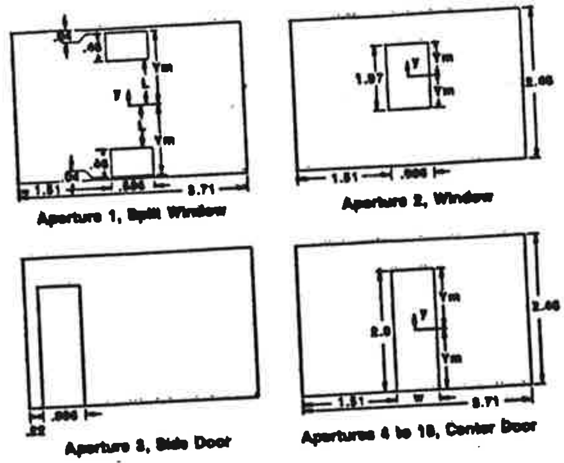

Fig. 3 Schematic of the common wall showing the aperture configurations tested

RESULTS AND DISCUSSION

Air Temperatures and Velocities

Typical air temperature and velocity data are presented in figures 5 through 8. The average value of air temperatures T_1 and T_2 were computed from the readings of the nine air temperature thermocouples in

Stratification of 8°/m !

each respective zone. These values of T_1 and T_2 were used to compute the values of zone-to-zone temperature difference, ΔT, and the overall average air temperature, $\bar{T}$. Figure 5 shows the zone-to-zone temperature difference ΔT for various elapsed times for four levels of heat input for aperture number 5, i.e., 0.686 m (27") wide center door. These data indicate

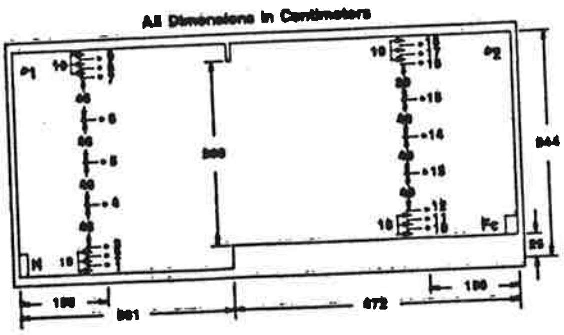

Fig. 4 Schematic floor plan of the step-up configuration for aperture numbers 9 and 10

that the value of ΔT drops rapidly during the first hour, and the rate of drop in the value of ΔT decreased with time as the air in the two zones mixes. Zone-to-zone temperature difference data for the other experiments was similar to the data shown in figure 5.

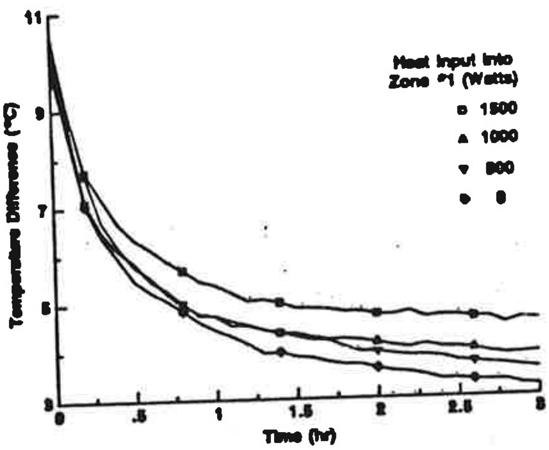

Fig. 5 Zone-to-zone temperature difference for various elapsed times for all four test conditions for 0.686 m wide center door

In figure 6, data taken 30 minutes after the start of the test are shown for the 0.686 m wide center door for a test with no heat input into zone #1. The instantaneous data are displayed on a north-south cross section of the experimental enclosure with the temperature scale located at the bottom of the figure and the zone height on the left side. In the center of the figure the aperture data is shown with the velocity scale located at the top of the figure. The aperture velocity distribution is represented by the solid line and the temperature distribution by the line marked with circles. The zone temperature distributions, monitored with a string of nine thermocouples in each zone, are displayed in the respective zone. These data indicate that the temperature distribution in both zones is non-linear. The data for other elapsed times for this aperture, and for other experiments, were similar to the data of figure 6.

The velocity of the outflow (i.e., the flow from warmer zone to the cooler zone) is taken as positive, while the velocity of the inflow is taken as a negative. Figure 7 shows aperture velocity

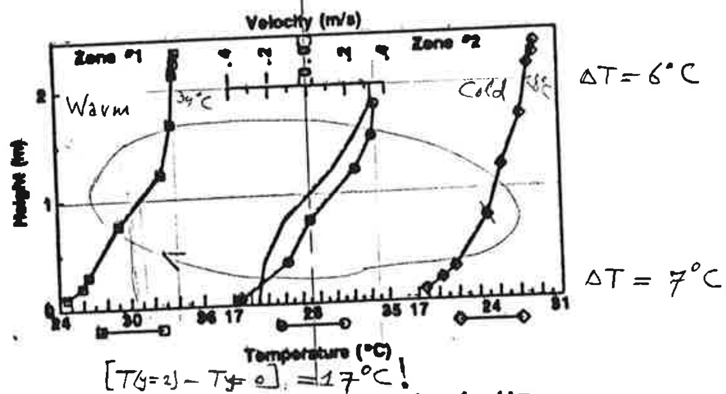

Fig. 6 Instantaneous temperature and velocity distribution for an elapsed time of 30 minutes, for 0.686 m wide center door with no heat input into zone #1 during the test

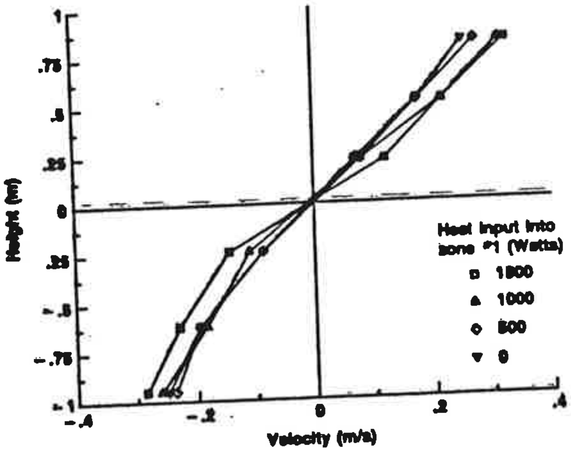

Fig. 7 Velocity distribution for an elapsed time of 30 minutes, for 0.686 m wide center door for all four test conditions

distribution for different experiments for the 0.686 m wide center door. These data were taken 30 minutes after the start of each experiment. These data indicate the outflow velocities are slightly higher than the inflow velocities and the neutral plane (i.e., the plane of zero velocity) is slightly above the geometric center of the aperture. The difference in the magnitude of velocities for different tests is due to the difference in the corresponding values of ΔT (figure 5).

Figure 8 shows the non-dimensionalized velocity data for an elapsed time of 30 minutes for .686 m and .914 m wide center doors for both the normal and step-up configurations. These data are from the experiments with 1500 watts of heat input into zone #1 during the tests. Equation (2), for a value of C = 0.55 is also plotted on figure 8 for the purpose of comparison. It is seen that the measured velocity distributions, due to the different boundary constraints, are different for the different apertures. The measured data for the center doors with step-up configuration are fairly symmetrical with respect to the neutral plane as predicted by equation (2). The velocities of the outflow for the doors in both configurations are very close to each other. However, the velocities of the inflow, particularly near the floor, for the step-up configurations are higher than those for normal configuration. As expected, the step-up configuration does modify the profile of the inflow. The data for

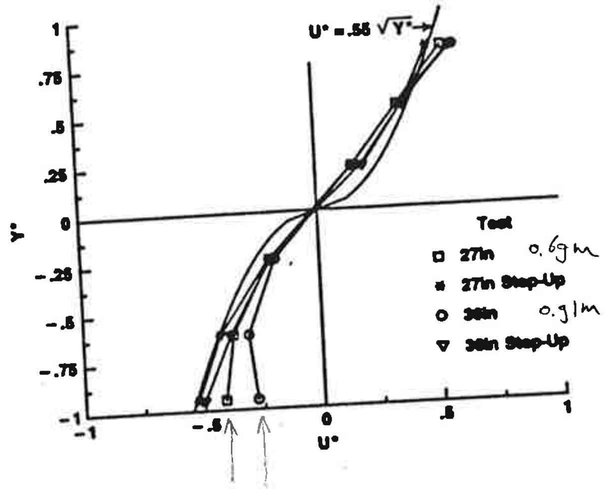

Fig. 8 Non-dimensional velocity for an elapsed time of 30 minutes, for 0.686 m and 0.914 m wide doors for both normal and step-up configurations

both doors with normal configuration show that due to curving of the streamlines the outflow velocity near the top edge of the aperture is higher than predicted by equation (2); while due to the no slip constraint at the floor the inflow velocity near the bottom edge of the aperture is lower than predicted by equation (2). These velocity profiles for center doors in the normal configuration are quite similar to the doorway velocity profiles measured during earlier experiments for a different test configuration [1-3].

Mass and Heat Flow Rates and Flow Coefficients

The experimental mass flow rates were computed from the velocity and temperature data taken at various heights in the aperture. The product of the local velocity, density and area was summed using trapezoidal summation techniques. The difference in the values of mass flow rates for the inflow and the outflow thus computed was 10% or less for all data. This difference in the values of the inflow and outflow is attributed to the difficulty in measuring low air speeds and unaccountable air infiltration elsewhere in the test enclosure. The experimental mass flow rate was non-dimensionalized by dividing it by the reference value of mass flow rate for the respective aperture. It should be noted that for the split window the quantity $(Y_m^{1.5})$ in equation (4) and (6) needs to be replaced with the quantity $(Y_m^{1.5} - L^{1.5})$. The measured values of zone-to-zone temperature difference, ΔT, and average temperature, T, were also non-dimensionalized by dividing these quantities with the respective reference quantities. Experimental heat flow rate was computed from the aperture velocity and temperature data, and non-dimensionalized.

Typical mass and heat flow rate data are shown in figures 9 through 12. The non-dimensionalized mass flow rate are plotted as functions of the quantity $(\Delta T^*/T^*)^{0.5}$, while non-dimensional heat flow rate data are displayed as functions of the quantity $(\Delta T^{*3}/T^*)^{0.5}$. A linear least square curve fitting technique was used to determine the values of aperture mass flow coefficient (i.e., the discharge coefficient), C, for equation (5) and aperture heat flow coefficient, C_q, for equation (8). The values of temperature correction coefficient, C_t, were computed from the values of C and C_q by using equation (10). The values of flow coefficients (C, C_q, and C_t) for all the experiments are given in Table 2.

Figures 9 and 11 respectively show mass and heat flow rate data for .686 m wide normal center door for all four test conditions. Figures 10 and 12 respectively show mass and heat flow rate data for .686 m and .914 m wide center doors for both the normal and step-up configurations for tests with no heat input into zone #1 during the test. The values of the flow

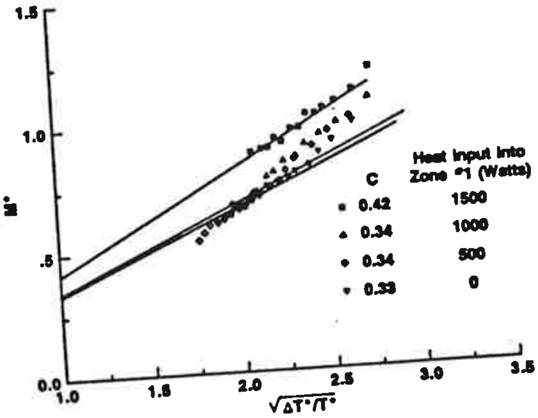

Fig. 9 Non-dimensional interzonal mass flow rate as a function of non-dimensional zone-to-zone temperature difference, for 0.686 m wide center door for all four test conditions

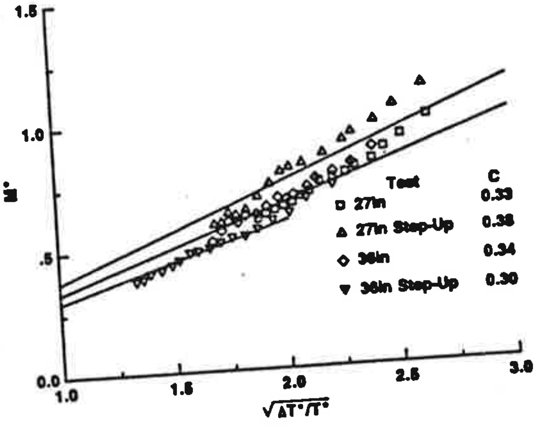

Fig. 10 Non-dimensioanl interzonal mass flow rate as a function of non-dimensional zone-to-zone temperature difference, for 0.686 m and 0.914 m wide doors for both normal and step-up configurations with no heat input to zone #1

coefficient computed from the data are also shown on these figures. These data indicate that the aperture mass and heat flow rates could have been adequately predicted by equation (5) and (8) respectively if the proper values of flow coefficients were known.

The data presented in Table 2 indicate that the values of the flow coefficients are dependent upon the aperture configuration, the test conditions (i.e. the heat input to the warmer zone), and the aperture area to wall area ratio. The values of flow coefficient for a center door with normal configuration are somewhat different than those for a center door of the same width in the step-up configuration. These values are also different than those for a side door of the same width. The differences in the values of flow coefficients probably result from the changes in the local flow patterns induced by the aperture configuration. The available data are too few to draw any clear conclusions.

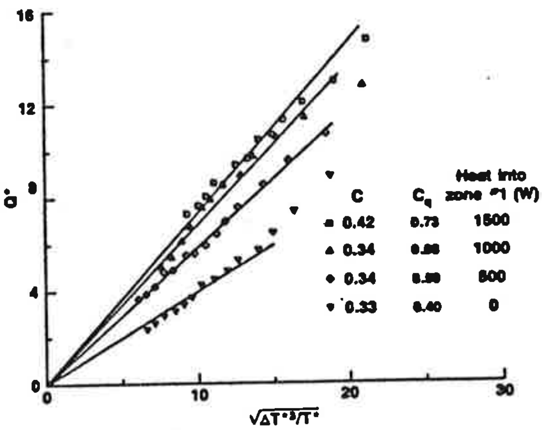

Fig. 11 Non-dimensional interzonal heat flow rate as a function of non-dimensional zone-to-zone temperature difference, for 0.686 m wide center door, for all four test conditions

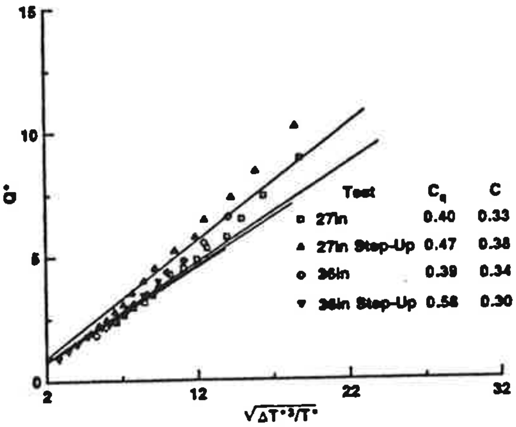

Fig. 12 Non-dimensional interzonal heat flow rate as a function of non-dimensional zone-to-zone temperature difference, for 0.686 m and 0.914 m wide doors for both the normal and step-up configurations with no heat to zone #1

The data of table 2 show that the value of the flow coefficients, C and C_q, generally, increase with an increase in the heat input to the warmer zone during the tests; because the addition of heat to zone #1 during the test affects the zone and aperture temperature distribution. The values of the temperature correction coefficient, C_t, for the window are much less than the values of C_t for other apertures. For the window, the values of C_t are all nearly equal to unity except for the test with no heat supply to zone #1 during the test. Because of the central location of the window, it seems reasonable that the zone temperature distribution has little or no effect on C_t. The values of C_t for all other apertures are greater than unity; and the value of C_t is larger for the tests with heat input to zone #1 than for the tests with no heat supply.

The value of C_t given in Table 2 shows that the variation in the value of C_t with increase in the

Table 2. Values of flow coefficients C, C_q, and C_t determined from data for different tests

Number Designation	Aperture Description	Aa/Aw	Values of C for different heat inputs to zone #1: 0W	500W	1000W	1500W	Values of C_q for different heat inputs to zone #1: 0W	500W	1000W	1500W	Values of Ct for different heat inputs to zone #1: 0W	500W	1000W	1500W
1	split-window	.069	.47	.53	.58	.59	.69	1.01	.94	.93	1.47	1.89	1.60	1.34
2	window	.080	.49	.53	.58	.58	.40	.58	.56	.54	.83	1.09	.97	.93
3	side-door	.150	.36	.38	.39	.48	.44	.67	.65	.76	1.44	1.76	1.66	1.87
4	(4-8) center-	.111	.39	.40	.43	.47	.54	.85	1.10	1.12	1.22	1.71	1.75	1.65
5	doors normal	.150	.33	.34	.34	.42	.40	.59	.68	.73	1.20	1.72	2.01	1.75
6	configuration	.200	.34	.32	.32	.38	.39	.58	.68	.70	1.13	1.81	2.21	1.83
7		.267	.23	.21	.21	.16	.25	.36	.51	.38	1.09	1.72	2.45	2.40
8		.300[1]	-	-	-	-	-	-	-	-	-	-	-	-
9	(9, 10) center-doors step-up	.150	.38	.41	.46	.49	.47	.78	1.01	.83	1.23	1.89	2.18	1.69
10		.200	.30	.34	.36	.46	.38	.65	.99	.94	1.26	1.91	2.76	2.05
11	center-door FY 1985 tests with high ceiling	.07[2]	.47	-	-	.32	.43	-	-	.72	.91	-	-	1.38

$C_q = C \times C_t$

1. No data for this aperture; the flow velocities were too low to measure.
2. Data from previous tests, the experimental configuration was different, as the tests were conducted using cell #2 as the warmer and cell #3 as the cooler of the two zones.

amount of heat input to zone #1 does not display a clear trend. It appears that the location of the heaters with respect to the aperture, also effects the value of C_t. This probably is because the different locations of heat input modify the temperature in Zone #1 and the aperture differently. The available data are too few to establish any clear relationship between the flow coefficients and the amount of heat input to the warmer zone during the test.

The average values of the four test conditions for the flow coefficients C and C_q are shown in Figure 13 as functions of A^*. The data of Figure 13 yielded

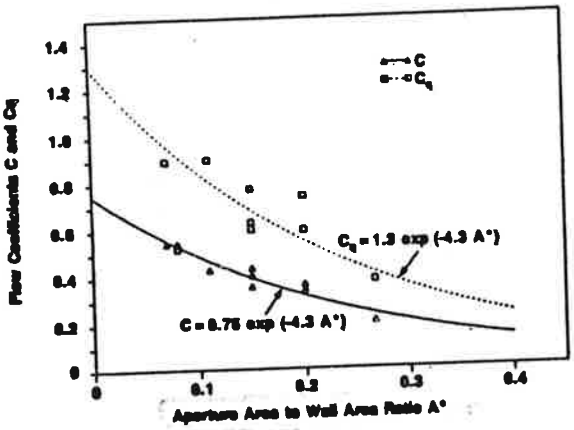

Fig. 13 Flow coefficient, C and C_q, as functions of aperture area to wall area ratio

the following relationships between the flow coefficients and A^*. The value of C_q for the window (i.e. aperture #2 of Tables 1 and 3), although shown in the figure, was not included during curve fitting the C_q data. For the window the values of C and C_q are approximately equal to each other.

$$C = 0.75 \exp(-4.3A^*) \quad (11)$$

$$C_q = 1.3 \exp(-4.3A^*) \quad (12)$$

Equation (11) and (12) are also plotted on figure 13 for the purpose of comparison. The data of Table 2 and Figure 13 show that the flow coefficients C and C_q increase with a decrease in the value of aperture area to wall area ratio (A^*).

CONCLUSIONS

Based on the data presented, the following statements may be made. The interzonal natural convection can be adequately predicted by the one-dimensional model for any aperture configuration for a two zone-set-up if the appropriate values of the flow coefficients, C, C_q, and C_t are known. The flow coefficients (C and C_q) increase with a decrease in the aperture area to wall area ratio. The flow coefficients generally increase with an increase in the heat input to the warmer zone during the test; but the data are too few to develop any useful relationship. The temperature correction coefficients are dependent on the aperture configuration as well as on the location and the quantity of the heat input to the warmer zone during the test; the data are too few to develop any clear relationships. Further experimental research may provide data that are useful for developing clear relationships between the flow coefficients, C, C_q and C_t, and aperture configuration and test conditions.

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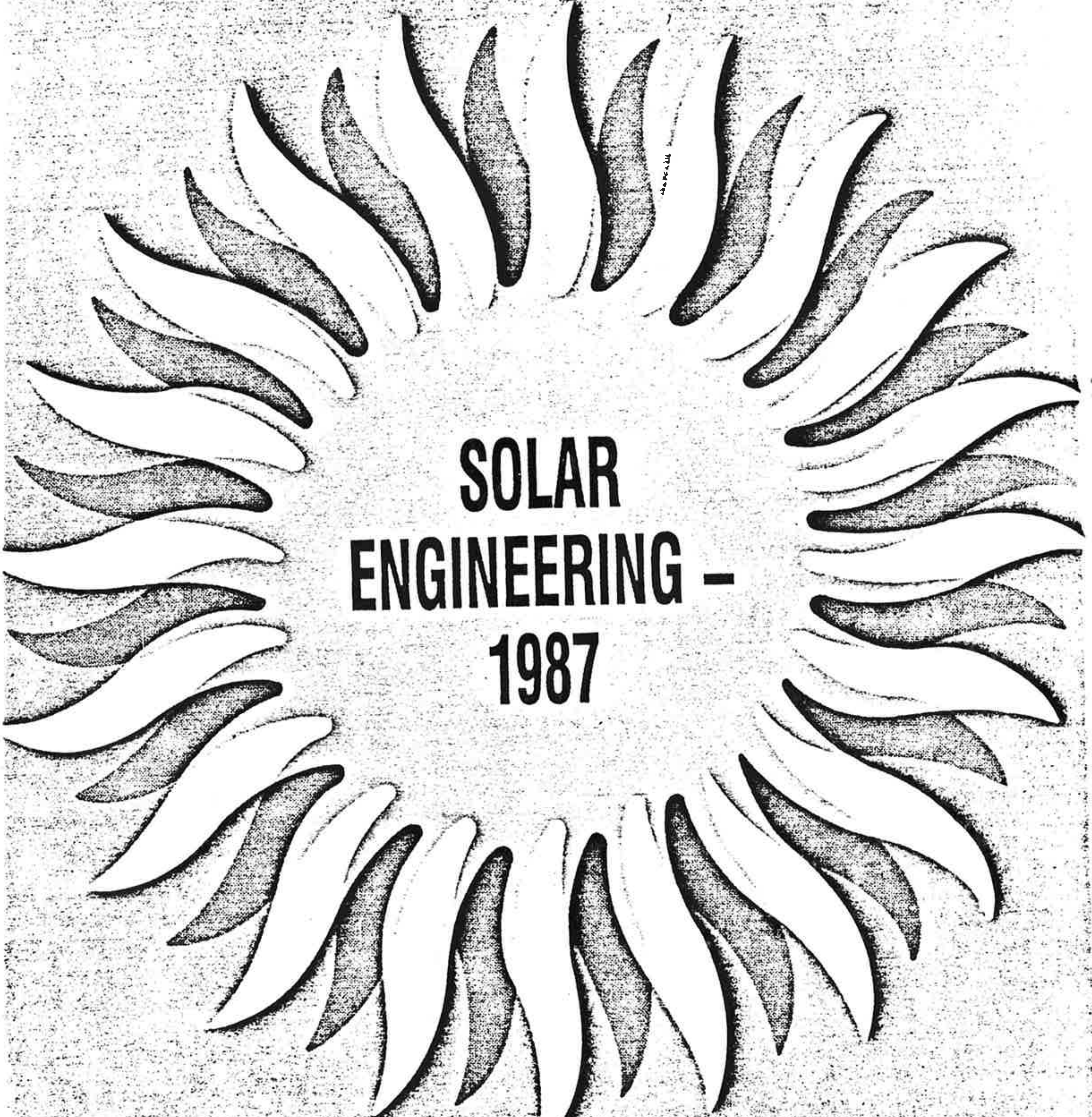

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