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Interzonal Natural Convective Heat and Mass Flow Through Doorway-Like Apertures in Buildings: Experimental Results

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This paper presents the results of full-scale experiments in a realistic building to evaluate natural convective heat and mass transfer through doorway-like apertures under small temperature differentials. The zone-to-zone temperature differences were nominally between 1°C and 2.5°C. Heat transfer correlations, coefficient of discharge, and thermal stratification are reported for air (Pr = 0.71), an enclosure aspect ratio of 0.26, aperture height relative to the enclosure height in the range of 0.75 to 1, and aperture width relative to the enclosure width in the range 0.29 to 0.79. In general, the results extends the validity of previous theoretical and experimental work in the literature to large doorway-like apertures and small temperature differentials across the aperture typical of residential building conditions.

Introduction

Interzonal natural convective heat and air mass transfer through doorway-like apertures in vertical partitions is an important process by which thermal energy and indoor contaminants are transported from one zone (room) to another in buildings. The objective of this study was to experimentally evaluate the interzonal natural convective heat and mass transfer for various aperture configurations typical of a doorway under small temperature differential across the aperture in a realistic building. The air flows through the aperture were driven primarily by the zone-to-zone temperature difference or the so-called bulk-density driven flow.

Barakat (1987) and Anderson and Kreith (1987) presented a comprehensive review on interzone convective heat and mass transfer. Maas (1992) presented a recent review on convective heat and mass flow through large interior/exterior openings in buildings. Maas also presented the results of recent studies on the subject. Maas review indicted that the value of the coefficient of discharge, C_d, in the literature varied between 0.3 and 0.8. Table 1 compares typical C_d values and the parameters pertinent to a number of studies in the literature. The selected studies were limited to those involving interzonal natural convective heat and air mass flows through large apertures that are driven primarily by the zone-to-zone temperature differential. Table 1 also includes the parameters pertinent to this study.

Recent experiments by Boardman, III et al. (1989) examined the influence of aperture height and width on interzonal natural convection heat and mass transfer in a full-scale air-filled test cell enclosure. The test cell was a 2.44 m (8 ft) cube enclosure with an aspect ratio (enclosure height to enclosure length ratio) of 1. The test cell was divided into two zones by a vertical partition which was centered between a constant heat flux hot wall and an isothermal cold wall. The zone-to-zone temperature difference was assumed to be 30°C. In Boardman, III et al. experiments, the interzonal convective heat flow was under the influence of both the so-called bulk density flow regime and the so-called boundary layer flow regime.

In the present study, the experiments were conducted in a realistic building with an enclosure aspect ratio of 0.26. Both the hot wall and the cold wall were isothermal. The interzonal convective heat and mass flows were primarily under the influence of the so-called bulk density flow regime driven by small (1 to 2.5°C) zone-to-zone temperature differential typical of residential building conditions.

Brown and Solvason (1962) pioneered the research on natural convection through openings in partitions. They have theoretically described the process in terms of the Nusselt number, Nu_H, the Grashof number, Gr_H, and the Prandtl number, Pr, in the form

$$Nu_H = (C_d/3)\,(Gr_H)^{0.5}\,Pr \tag{1}$$

where C_d is the coefficient of discharge for the opening. Their theoretical analysis was based on the inviscid Bernoulli equation and the assumption that the air temperatures on either side of the aperture were uniform (i.e., no vertical temperature gradients). Recent studies, e.g., Kirkpatrick and Hill (1988) and Pelletret et al. (1991), indicated the importance of temperature stratification on the convective heat transfer through apertures.

Brown and Solvason experimentally determined C_d to be in the range 0.65 to 1.0. Their experiments involved air flow

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Table 1 Summary of a selected interzonal natural convection studies

Source	Enclosure Aspect Ratio	R_h	R_w	ΔT (°C)	R_t	C_d
Brown and Solvason (1962)	0.44	0.062-0.125	0.062-0.125	8 - 47 near partition	0.19-0.75	0.6-1.0
Shaw (1971)	0.84		(0.1 - 0.9 m)	3 - 10 at opening top & bottom	0.05	0.66
Shaw and Whyte (1974)		0.84	as above	1 - 10 room centre	0.05	0.8
Mahajan (1987)		doorway size opening (0.76 x 2.0 m)	room avg.	2.5 - 10	0.075	0.48-0.58
Maas (1992) and Pelletret (1991): Liege U. study	0.45	0.86	0.4	1.42 - 2.3 room avg.	0.046	0.33-0.42
INSA study	0.4	0.74	0.26	0.64-2.9 room centre		0.27-0.54
CSTB study	0.4	0.83	0.15	room avg.		0.28-1.07
This study	0.26	0.75-1.0	0.29-0.79	1 - 2.5 room centre room avg.	0.021-0.028	0.59-0.74 0.46-0.66

through single openings with a maximum size of 0.305 × 0.305 m. The temperature differentials across the opening were between 8.3 and 47.2°C. The partition thickness was relatively large and was in the range 0.19 to 0.75 of the opening height.

This study extends (see Table 1) the validity of the theory and results of Brown and Solvason to large opening sizes typical of doorways, small temperature differentials typical of residential building conditions, and relatively small partition thickness. The zone-to-zone temperature differences were nominally between 1°C and 2.5°C.

Aperture configurations included: aperture height relative to the enclosure height in the range of 0.75 to 1 and aperture width relative to the enclosure width in the range 0.29 to 0.79. Also studied is the thermal stratification in the cold and hot zones.

Several definitions of the characteristic temperature difference which is used in the evaluation of Grashof number have been reported in the literature:

- temperature difference between air near partition (Brown and Solvason, 1962),
- difference between air at top and bottom of aperture (Shaw, 1971),
- difference between air at the center of each zone at a level of half the aperture height (Shaw and Whyte, 1974). Shaw and Whyte selected this definition for practical reasons. However, they indicated that the characteristic temperature difference that led to the most accurate correlation of the convective heat flow was the difference between the mean temperature of the air flowing out of the warm zone and that flowing into the warm zone.
- difference between average air temperature in each zone (Mahajan, 1987; Mahajan and Hill, 1987),
- difference between hot and cold end walls (Nansteel and Greif, 1984; Lin and Bejan, 1983), and
- difference between average air temperature in each zone in range of aperture height (Yamaguchi, 1984).

In this study, the following definitions of the characteristic temperature difference were considered:

ΔT_a: difference between average air temperatures in each zone measured at a level of half the enclosure height,

ΔT_m: difference between air temperatures at the center of each zone at a level of half the enclosure height,

ΔT_v: difference between average air temperatures of a vertical grid of nine thermocouples at the center of each zone, and

ΔT_p: difference between average air temperatures of a vertical grid at the center of each zone in the range of the aperture height.

Nomenclature

C = constant in correlations
C_d = coefficient of discharge
C_p = specific heat of air (J/kg K)
D_h = hydraulic diameter of aperture (m), D_h = 4 × aperture area/aperture perimeter
F = volumetric air flow rate (m^3/s)
F_m = experimental volumetric air flow rate (m^3/s)
F_t = theoretical volumetric air flow rate (m^3/s)
g = gravitational acceleration, 9.81 (m/s^2)
Gr_H = Grashof number, $g\beta H^3 \Delta T/\nu^2$ (dimensionless)
h = convective heat transfer coefficient, $\rho F_m C_p / HW$ (W/m^2 K)
H = aperture height (m)
H_r = room (enclosure) height (m)
k = thermal conductivity of air (W/m K)
L = enclosure length (m)
Nu_H = Nusselt number, hH/k (dimensionless)
Pr = Prandtl number (dimensionless)
R_a = aperture area ratio, $HW/(H_r W_r)$
R_h = aperture height ratio, H/H_r
R_t = partition thickness ratio, t/H
R_w = aperture width ratio, W/W_r
t = partition thickness (m)
W = aperture width (m)
W_r = partition width (m)
ΔT_a = difference between average air temperatures in each zone measured at a level of half the enclosure height (°C)
ΔT_m = difference between air temperatures at the center of each zone at a level of half the enclosure height (°C)
ΔT_n = nominal temperature differential, difference between air temperatures at the thermostat location in each zone (°C)
ΔT_v = difference between average air temperatures of a vertical grid of nine thermocouples at the center of each zone (°C)
ΔT_p = difference between average air temperatures of a vertical grid at the center of each zone in the range of the aperture height (°C)
β = coefficient of thermal expansion (1/K)
ν = kinematic viscosity (m^2/s)
ρ = air density (kg/m^3)

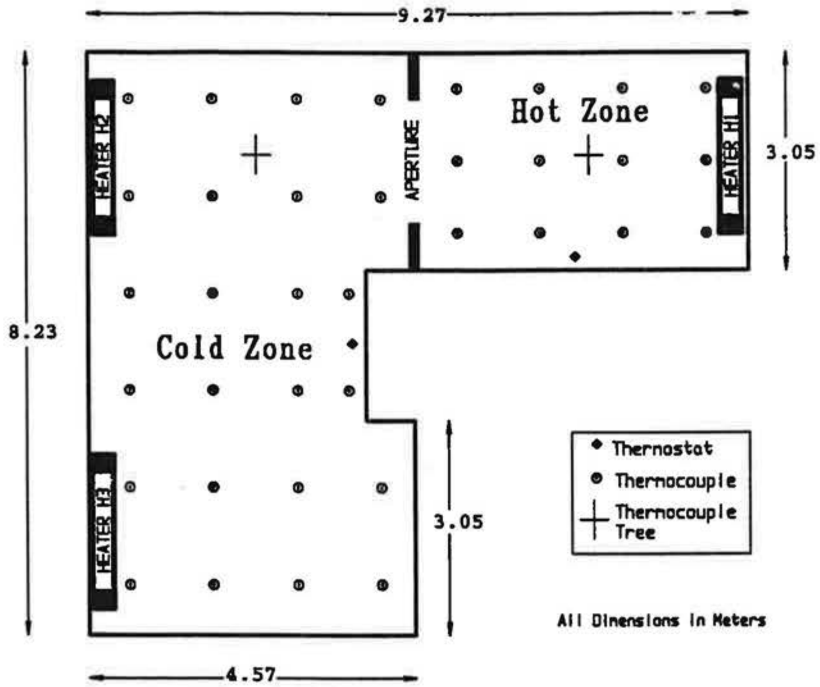

Fig. 1 Floor plan of test facility

Description of Experiments

The experiments were performed in a full-scale test house facility. Barakat (1984) describes the facility in detail. Figure 1 shows the floor plan of the test house. The aperture configuration is shown in Fig. 2. The partition wall separating the two zones was constructed of 0.05 m (2 in.) polystyrene which facilitated the construction of various aperture configurations. The hot zone measured about 4.572 m × 3.05 m (15 ft × 10 ft) and the cold zone measured about 4.572 m × 8.23 m (15 ft × 27 ft). The enclosure height of the test zones was 2.41 m (94.75 in.). The aperture was situated in the middle of the partition and did not have a sill. The aperture configurations are summarized in Table 2.

All interior surfaces of the test house were practically isothermal. Direct solar radiation was blocked from entering the two test zones. Three baseboard heaters were located at the back wall of each test cell (one in the hot room and two in the cold room); Fig. 1. The heaters were used to maintain nominal zone-to-zone temperature differences between 1°C and 2.5°C. Power consumption of each heater was measured with a kWh pulse meter. Heater data were recorded every 15 minutes and averaged every hour using a data logger. Heater data were collected for sake of completeness so that the measured data can be used to evaluate computational fluid dynamics based models as well as scale models.

The velocity and temperature distributions of the air at the aperture were measured with a vertical grid of 7 to 10[1] omnidirectional anemometers (type DANTEC 54R10) in conjunction with a DANTEC 24 channel multiflow analyzer. The accuracy of the omni anemometers was estimated to be ±2.5 percent for the velocity range 0.05–1.0 m/s and the absolute accuracy of temperature measurements was ±0.5°C. The omni probes tree was positioned at between two to four[2] different locations along the width of the aperture (in one-half the width); Fig. 2. A preliminary traverse across the full width of the aperture had indicated symmetrical conditions on either side of the aperture center line.

[1]depending on the aperture height

[2]depending on the aperture width

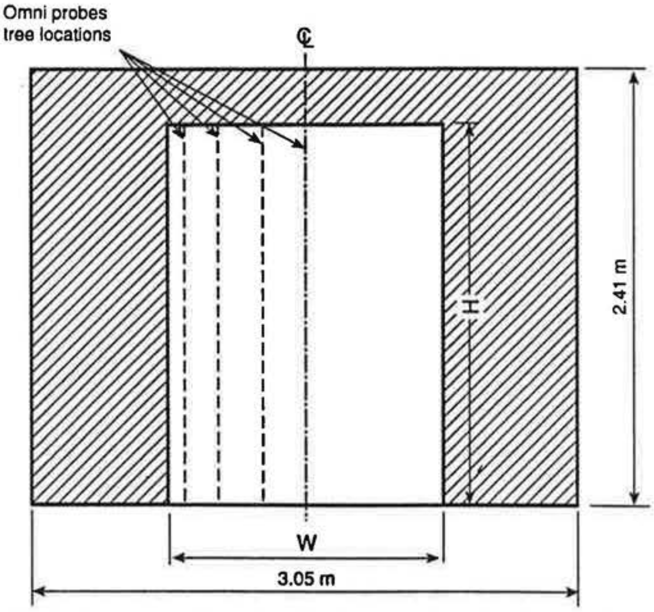

Fig. 2 Aperture configuration showing typical omni probes tree locations

Trees consisting of nine copper-constantan thermocouples were located at the center of each zone along the center line of the aperture (Fig. 1). The readings of these thermocouples were used to compute the average temperature, T_v, at the center of each zone. In addition, 36 thermocouples were mounted in various locations (Fig. 1) in both zones at a level of half the enclosure height. The readings of these thermocouples were used to evaluate the average air temperature, T_a, in each zone. Air temperature was also measured at the typical thermostat location/level in each zone (see Fig. 1). The difference between these two measurements was used to determine the nominal temperature differential for each test. The air temperatures in surrounding rooms and outdoors were also monitored. The maximum uncertainty in measured temperatures by the copper-

Table 2 Test configurations

Test	W (m)	H (m)	Aperture R_w	R_h	R_a	Temperature Differential (°C) ΔT_n	ΔT_a	ΔT_v	ΔT_m	ΔT_p
A	1.49	2.41	0.49	1.00	0.49	1.8	1.78	1.14	1.2	1.14
B	1.49	2.11	0.49	0.88	0.43	2.5	2.23	1.4	1.67	1.41
C	1.49	1.81	0.49	0.75	0.37	2.5	2.03	1.27	1.61	1.25
D	0.88	2.41	0.29	1.00	0.29	2.5	2.23	1.59	1.86	1.59
E	0.88	2.11	0.29	0.88	0.25	2.5	2.32	1.67	2.07	1.69
F	0.88	1.81	0.29	0.75	0.22	2.5	2.54	1.95	2.31	1.95
G	0.88	2.41	0.29	1.00	0.29	1.0	1.07	0.79	0.7	0.79
H	0.88	2.11	0.29	0.88	0.25	1.0	1.07	0.74	0.62	0.7
I	1.49	1.81	0.49	0.75	0.37	1.1	1.2	0.78	0.76	0.71
J	2.41	2.11	0.79	0.88	0.69	1.0	1.24	0.62	0.75	0.57

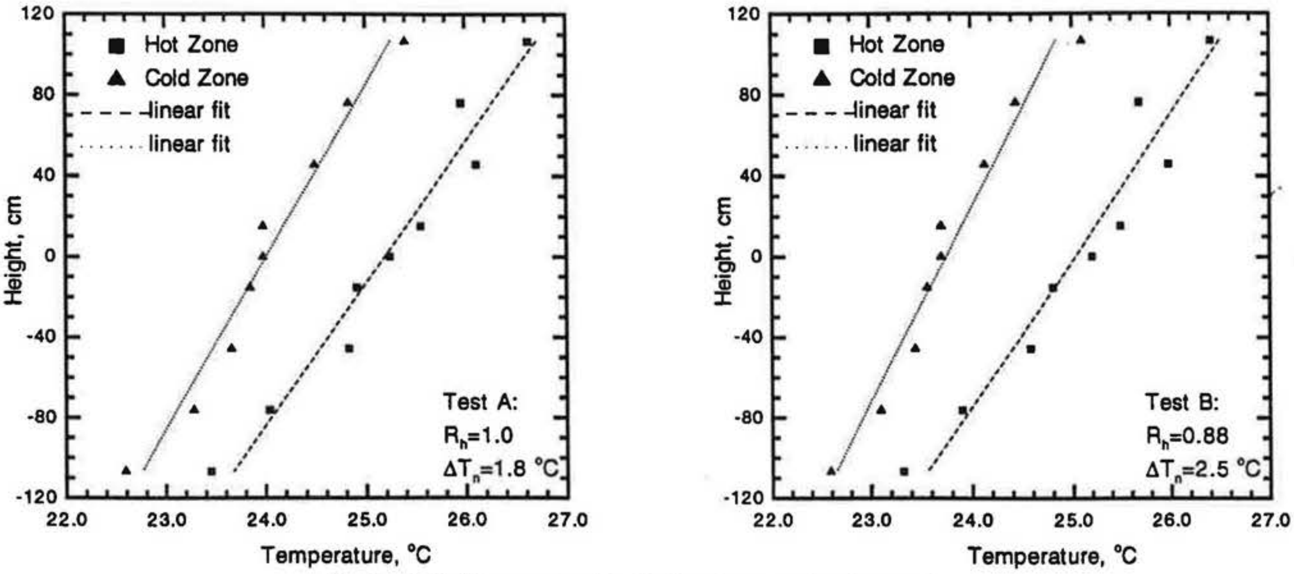

Fig. 3 Vertical temperature distribution at center of each zone; R_w = 0.49

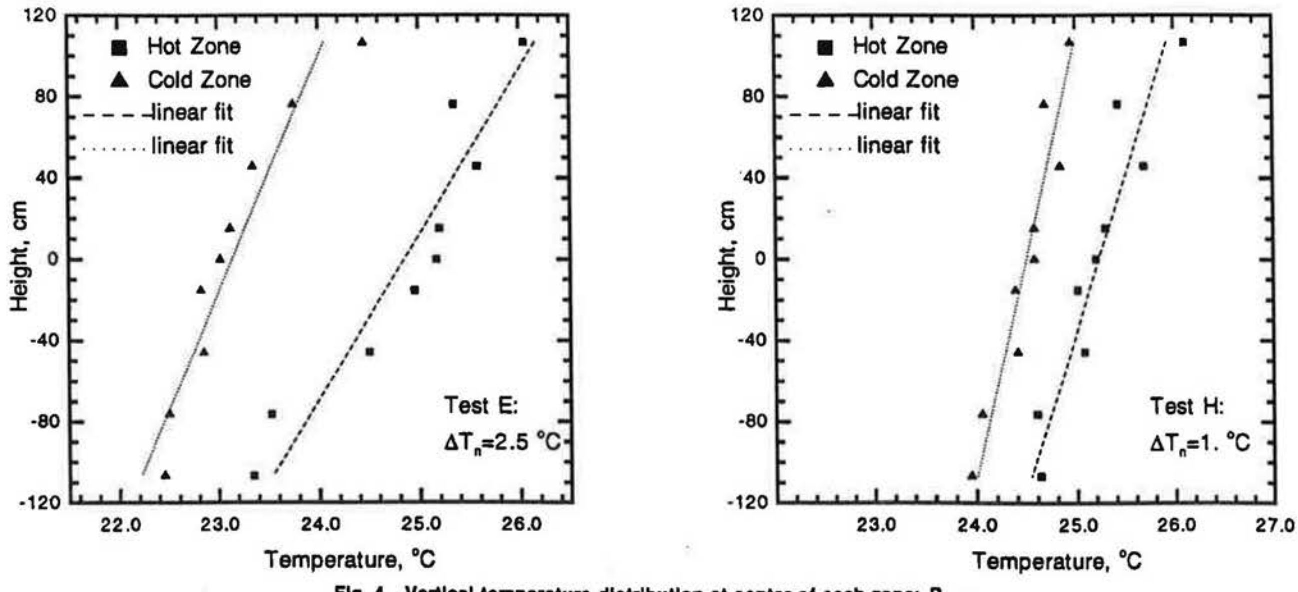

Fig. 4 Vertical temperature distribution at center of each zone; R_w = 0.29, R_h = 0.88

constantan type thermocouples was estimated to be ± 0.1°C. Measurements were collected continuously over at least a 24-h period. Steady-state conditions were designated when there was negligible change in room air temperatures for at least four hours. The results were then averaged over a 12-h steady-state period.

Results and Discussion

Temperature and Velocity Distributions. Figures 3 and 4 show typical vertical distributions of the air temperature at the center of each of the hot and cold zones. Linear regression was used to evaluate thermal stratification (vertical temperature gradient) in each zone. Average thermal stratifications (Table 3) were between 0.65 and 1.33°C/m at the hot zone center and between 0.47 and 1.0°C/m at the cold zone center. The lower level of thermal stratification being for the tests with the lower zone-to-zone temperature difference (ΔT_n = 1.0°C). Test J is exceptional because this test involved the largest aperture width, R_w = 0.79, and it was difficult to maintain the zone-to-zone temperature differential.

Figures 5 to 8 show typical vertical distributions of the air temperature and velocity at various locations along the width of the aperture. The velocity of the air flowing out of the hot zone to the cold zone is taken as positive and vice versa. For all tests, except that with the large aperture width (R_w = 0.79), the neutral plane (the plane of no horizontal flow) was very close to the midheight of the aperture. For each aperture, the vertical profiles of the air temperature and velocity along the width of the aperture, for most part, form a single family (Figs. 5 to 8). This indicates a fairly uniform width-wise distribution of the air velocities and temperatures at the aperture. It is also noted that the velocity profiles are fairly similar to the theoretical velocity profile based on the inviscid Bernoulli equation by Brown and Solvason (1962) which indicates that the interzone convection flows were dominated by bulk density difference between the two zones. The vertical velocity distributions at the aperture are much more symmetric than the temperature distributions with respect to the neutral plane.

Table 3 Thermal stratification (S), °C/m

ΔT_n (°C)	Hot Zone		Cold Zone	
	S	R^2	S	R^2
2.5	1.33	0.88-0.94	1.0	0.74-0.96
1.0	0.65	0.88	0.47	0.91
1.0 °C, R_w=0.79	1.1	0.95	0.65	0.95

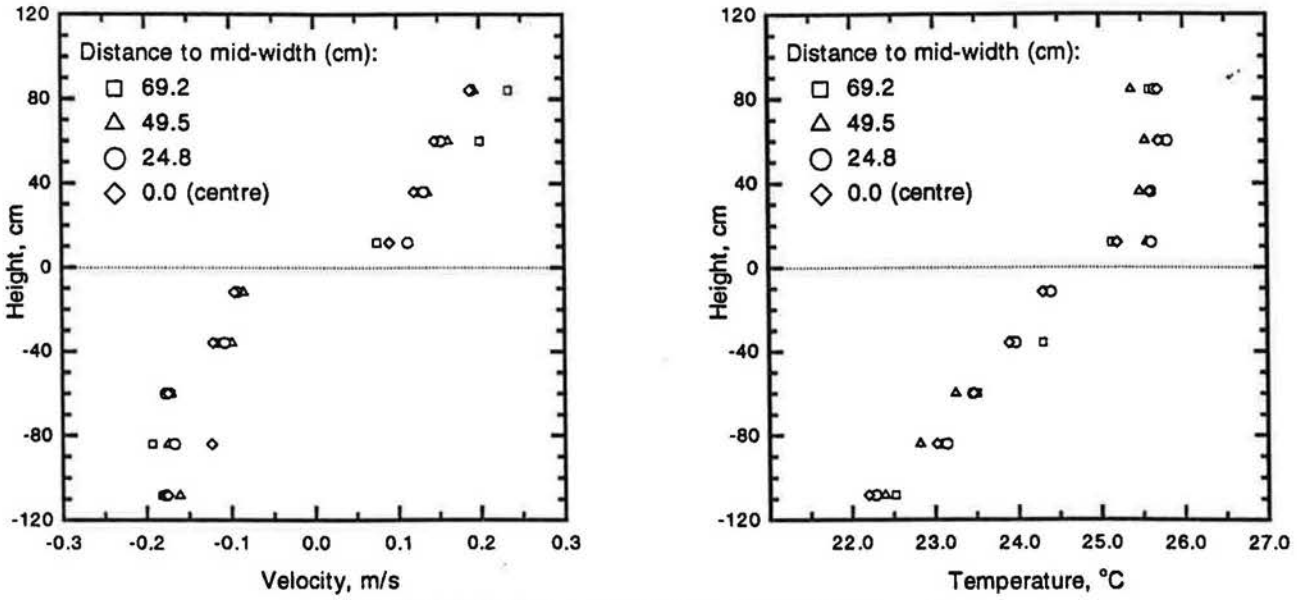

Fig. 5 Vertical distributions of velocity and temperature at aperture; R_w = 0.49, R_h = 1.0, ΔT_n = 1.8°C (Test A)

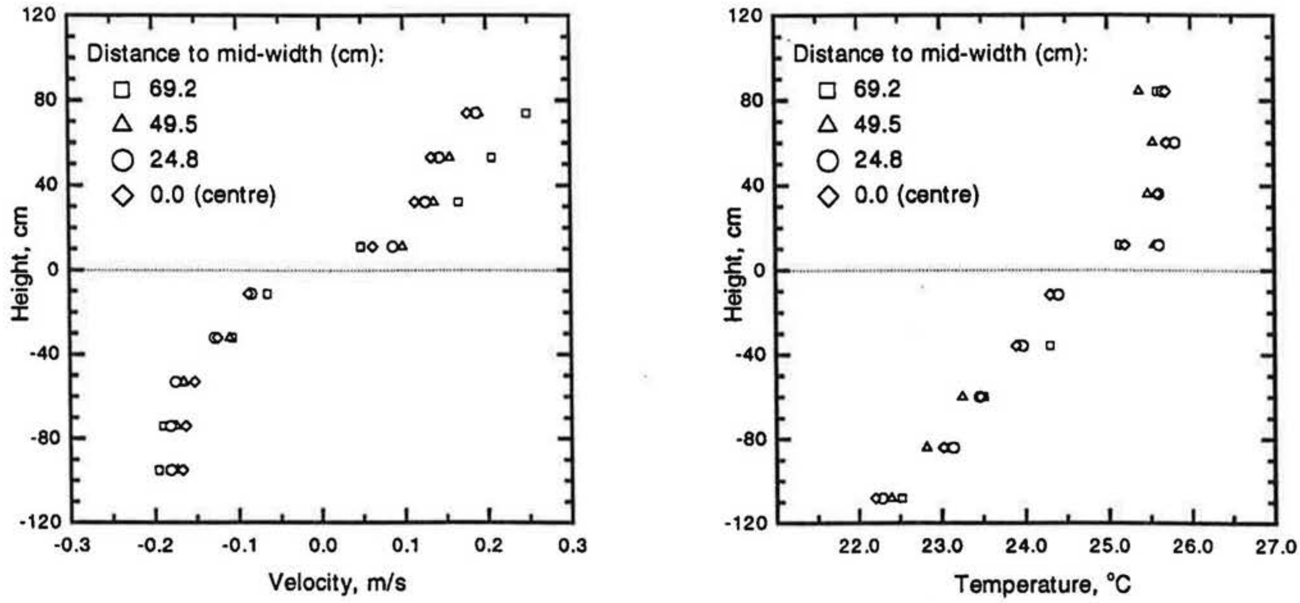

Fig. 6 Vertical distributions of velocity and temperature at aperture; R_w = 0.49, R_h = 0.88, ΔT_n = 2.5°C (Test B)

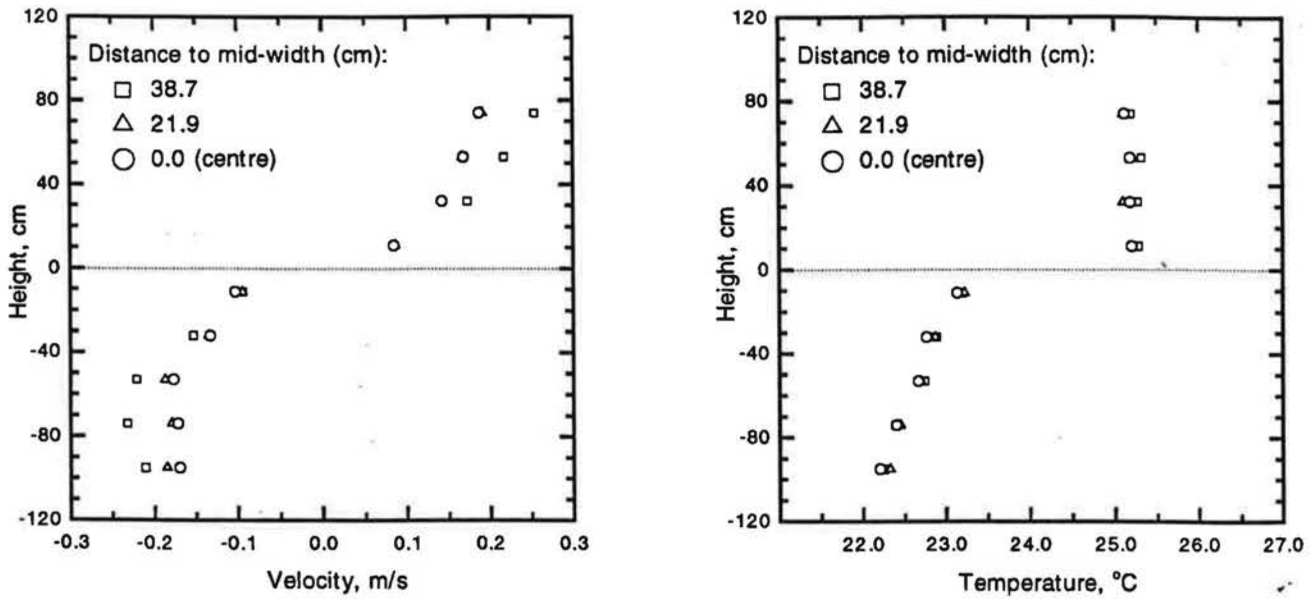

Fig. 7 Vertical distributions of velocity and temperature at aperture; R_w = 0.29, R_h = 0.88, ΔT_n = 2.5°C (Test E)

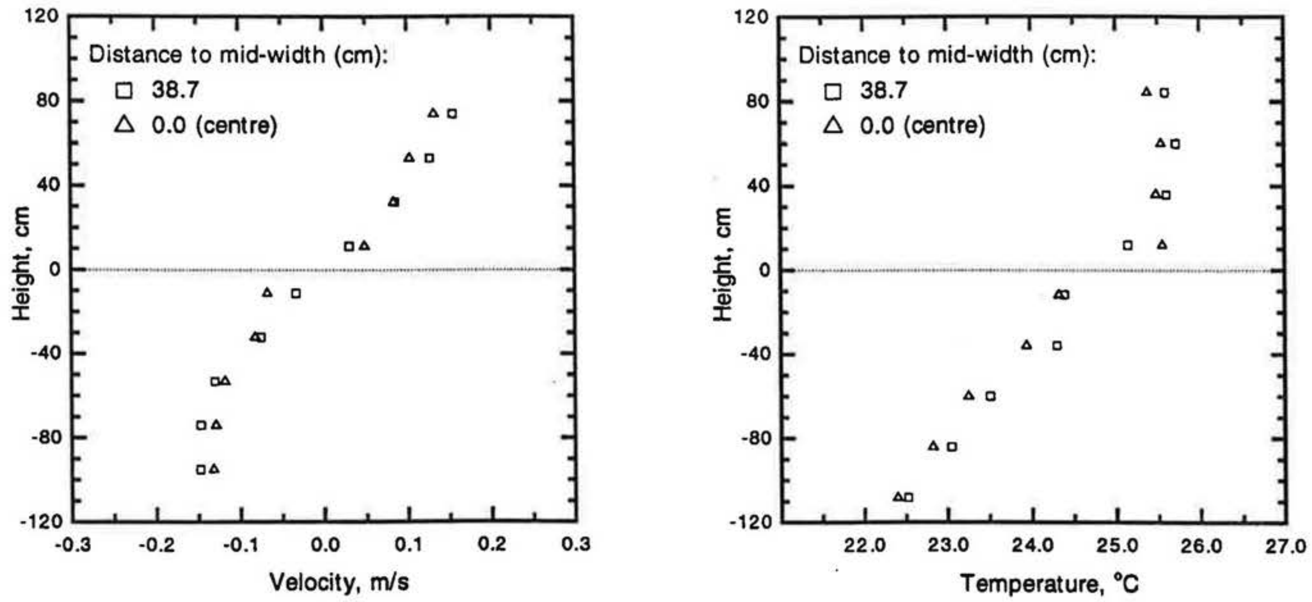

Fig. 8 Vertical distributions of velocity and temperature at aperture; R_w = 0.29, R_h = 0.88, ΔT_n = 1.0°C (Test H)

Above the neutral plane, the temperature profiles suggest good mixing conditions in that part of the aperture. Below the neutral plane, the temperature profiles at the aperture (Figs. 5 to 8) are very similar to that in the cold zone (as shown in Figs. 3 and 4) which is consistent with the convective flow of stratified cooler air from the cold zone to the hot zone.

Coefficient of Discharge. The volumetric flow rate through one-half the aperture (with respect to the neutral plane) was computed by summing the product of local velocity and area. For all tests, except Test C, the difference between the computed volumetric flow rates of air out of the hot zone and that into the hot zone was at most 12 percent. For Test C, the difference was 31 percent. The air mass flow rates out of and into the hot zone, computed by summing the product of local density and local volumetric flow rate, differed by one percent in all cases. This was expected because, as noted earlier, the neutral plane location was very close to the midheight of the aperture and also the velocity profiles were symmetric with respect to the neutral plane. The theoretical volumetric flow rate, F_t, was calculated with the relation derived by Brown and Solvason (1962),

$$F_t = (W/3)(g\beta H^3 \Delta T)^{0.5}, \tag{2}$$

where the symbols are as defined in the Nomenclature. The fluid properties were taken at the overall mean air temperature of both zones.

The volumetric coefficient of discharge, C_d, was then calculated from the experimental volumetric flow rate, F_m, over the theoretical one, F_t. The values of C_d were found to be in the range 0.46 to 0.75, with considerable dependence on the definition of the characteristic temperature difference ΔT (see Table 4). Using ΔT_v resulted in C_d values in the range of 0.63 to 0.75 which are consistent with those by Brown and Solvason (1962). As expected, over the range of aperture configurations and temperature differentials studied, both ΔT_v and ΔT_p gave almost the same results. Because of the large aperture height ratios, ΔT_v values were very close to ΔT_p values (see Table 2).

Using an average C_d value of 0.66 in conjunction with Eq. (2) gives

$$F = 0.22W(g\beta H^3 \Delta T)^{0.5}. \qquad (3)$$

Using ΔT_v, ΔT_p or ΔT_m, Eq. (3) correlates very well (R^2 = 0.92) with the experimental volumetric air flow rates for all the range of aperture configurations and temperature differentials studied. Similarly, for ΔT_a, a C_d value of 0.57 correlates all the experimental data with R^2 = 0.86.

Nusselt Correlations. The natural convective heat flow rate through the aperture was computed from the experimental air mass flow rate through the aperture and the temperature differential across the aperture. The results are presented in terms of Nusselt numbers. Six Nusselt correlation equations were considered:

$$\mathrm{Nu} = C\,\mathrm{Gr}^b\mathrm{Pr} \qquad (4)$$

$$\mathrm{Nu} = C\,\mathrm{Gr}^{0.5}\mathrm{Pr} \qquad (5)$$

$$\mathrm{Nu} = C\,R_h^a\mathrm{Gr}^b\mathrm{Pr} \qquad (6)$$

$$\mathrm{Nu} = C\,R_a^a\mathrm{Gr}^b\mathrm{Pr} \qquad (7)$$

$$\mathrm{Nu} = C\,R_w^d\mathrm{Gr}^b\mathrm{Pr} \qquad (8)$$

$$\mathrm{Nu} = C\,R_h^aR_w^d\mathrm{Gr}^b\mathrm{Pr} \qquad (9)$$

Correlation Eq. (5) is the theoretical form, (Eq. (1)) by Brown and Solvason (1962) in which the coefficient C = $C_d/3$. The aperture height, H, was selected as the characteristic length in Nu and Gr numbers. Table 5 lists the coefficient C and the exponents a, b, and d for the six correlation equations.

The hydraulic diameter of the aperture, D_h, was also considered but it caused a significant decrease in the goodness of fit (R^2 = 0.43–0.91) for correlation Eqs. (4) to (7). However, Eqs. (8) and (9) correlated the experimental data fairly well (R^2 = 0.85–0.96). In general, the choice of the definition of the temperature difference had little effect on the goodness of fit for the correlations in which the aperture height was used as the characteristic length. However, when the hydraulic diameter of the aperture was used, the correlations were sensitive to the definition of the characteristic temperature difference.

As shown in Table 5, the characteristic temperature difference that led to the most accurate Nu correlation (R^2 = 0.94 to 0.96) was the difference between average air temperatures of the vertical grid at the center of each zone, ΔT_v. However, a close goodness of fit, R^2 = 0.93–0.94, was obtained using ΔT_m and ΔT_a. The latter temperature differential ΔT_a (the difference between average air temperatures in each zone measured at a level of half the enclosure height) is commonly used by building energy simulation computer programs. The temperature differential ΔT_m (the difference between air temperatures at the center of each zone at a level of half the enclosure height) is, however, convenient to measure in practice. Thus, the following discussion is limited to the results in which ΔT_m was used.

It is noted from Table 5 that (including the aperture height ratio in the correlation) Eq. (6) improved the goodness of fit slightly compared to Eqs. (4) and (5). As expected, the aperture width ratio did not affect the goodness of fit of the correlation (Eqs. (7) and (8)). In the correlation Eq. (4), the exponent of Gr is very close to the theoretical value of 0.5 of Brown and Solvason (1962). This extends the validity of their theory to doorway-like apertures and small temperature differentials across the aperture typical of residential building conditions. The value of the coefficient C, 0.222, in correlation Eq. (5) is also consistent with that of Brown and Solvason. Thus this correlation was confirmed to be the appropriate simple choice. Figure 9 shows this equation together with the experimental data and the lower and upper limits (C = 0.2 and 0.33) by Brown and Solvason. Figure 9 also shows the experimental data and the corresponding Eq. (5) in which ΔT_v was used.

Figure 10 shows the dependence of Nu on aperture height ratio, R_h, and zone-to-zone temperature difference, ΔT_m. The Nusselt number increases as R_h and ΔT_m increase. Because of the limited number of tests and the combination of aperture configuration and zone temperature difference, it was difficult to isolate the effect of the aperture width on Nu results. However, the influence of the aperture width has been studied by many authors and found little effect (e.g., Neymark et al., 1989). Neymark et al. indicated that Nu is not a strong function of the aperture width until the dimensionless aperture width (R_w) is less than 0.1.

Table 4 Coefficient of discharge results for various ΔT's

Test	C_d (ΔT_a)	C_d (ΔT_v)	C_d (ΔT_m)	C_d (ΔT_p)
A	0.60	0.75	0.74	0.75
B	0.58	0.73	0.67	0.73
C	0.52	0.66	0.59	0.66
D	0.59	0.70	0.65	0.70
E	0.62	0.74	0.66	0.73
F	0.66	0.75	0.69	0.75
G	0.54	0.63	0.67	0.63
H	0.60	0.72	0.78	0.74
I	0.51	0.64	0.65	0.67
J	0.46	0.65	0.59	0.68

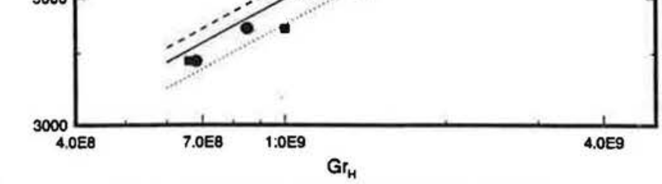

Fig. 9 Nusselt number versus Grashof number

Table 5 Correlation results for characteristic length H (aperture height)

Nu Equation	ΔT_a C	ΔT_a a	ΔT_a b	ΔT_a d	ΔT_a R^2	ΔT_v C	ΔT_v a	ΔT_v b	ΔT_v d	ΔT_v R^2	ΔT_m C	ΔT_m a	ΔT_m b	ΔT_m d	ΔT_m R^2
4) $C\,Gr^bPr$	.048		.565		.93	.078		.553		.95	.382		.475		.93
5) $C\,Gr^{0.5}Pr$	.195				.93	.235				.94	.222				.93
6) $C\,R_h^aGr^bPr$	.011	-0.3420	.631		.95	.018	-0.327	.619		.96	.835	.27	.44		.94
7) $C\,R_a^aGr^bPr$	0.034	-0.117	.574		.93	.076	.019	0.553		.95	.383	.026	.476		.93
8) $C\,R_w^dGr^bPr$	.054		.555	-0.088	.95	.064		.564	.056	.95	.395		.473	-0.012	.93
9) $C\,R_h^aR_w^dGr^bPr$	.01	-0.378	.629	-0.099	.95	.016	-0.325	.628	.065	.96	.845	.269	.439	-0.007	.94

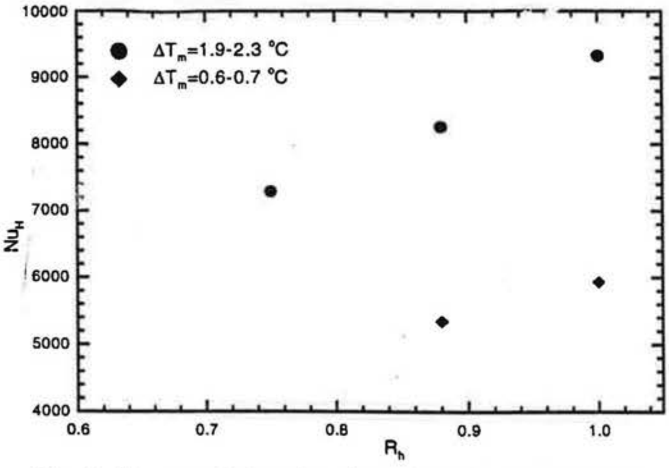

Fig. 10 Nu versus R_h for selected experimental data (R_w = 0.29)

Conclusions

Results of full-scale experiments in a realistic building to evaluate interzonal natural convective heat and mass flows through doorway-like apertures have been presented for an enclosure aspect ratio of 0.26, aperture height relative to the enclosure height of 0.75 to 1, aperture width relative to the enclosure width of 0.29 to 0.79, and zone-to-zone temperature differential of 1°C to 2.5°C. The interzonal natural convective flows were primarily under the influence of the so-called bulk density flow regime.

The results of this study indicate that:

- Average thermal stratification varied between 0.65 and 1.33°C/m in the hot zone center, and between 0.47 and 1.0°C/m in the cold zone center with the lower levels being for the tests with 1°C zone-to-zone temperature differential.
- For the aperture configurations and conditions tested, the neutral plane was very close to the midheight of the aperture. The measured velocity profiles at the aperture were similar to the theoretical velocity profile based on the inviscid Bernoulli equation by Brown and Solvason (1962). The results of this study extends the validity of Brown and Solvason's inviscid flow model to doorway-like apertures and small temperature differentials typical of residential building conditions.
- Coefficients of discharge were found to range between 0.46 and 0.75, with considerable dependence on the definition of the temperature differential across the aperture. An average C_d value of 0.66 correlates very well with all the experimental data when ΔT_v, ΔT_p or ΔT_m is used. For ΔT_a, an average C_d value of 0.57 correlates well with all the experimental data.
- Interzonal natural convective heat and mass transfer through a doorway-like aperture (under the influence of bulk density flow regime) can accurately be described by the following theoretically derived equations and experimentally determined coefficients:

$$Nu_H = 0.222\ Gr_H^{0.5}\ Pr, \quad \text{for } \Delta T = \Delta T_m \tag{10}$$

$$F = 0.22\ W(g\beta H^3 \Delta T)^{0.5}, \quad \text{for } \Delta T = \Delta T_v,\ \Delta T_p \text{ or } \Delta T_m \tag{11}$$

$$F = 0.19 W(g\beta H^3 \Delta T)^{0.5}, \quad \text{for } \Delta T = \Delta T_a \tag{12}$$

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