To be pub
Applied energy

#4998

A REVIEW OF ALGORITHMS FOR AIRFLOW THROUGH LARGE OPENINGS

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ABSTRACT

The present paper reviews results of research into airflow through large internal and external openings. A brief description of experimental work and algorithms developed by various researchers is presented. The paper also outlines requirements to improve existing airflow algorithms.

NOTATION

A	Area of the opening (m^2)
B	Zone width (m)
C_D	Coefficient of discharge (dimensionless)
c_p	Specific heat (kJ/kg K)
C_p	Pressure coefficient (dimensionless)
C_T	Coefficient of temperature (dimensionless)
C_v	Coefficient of velocity (dimensionless)
F	Volumetric flow rate (m^3/s)
g	Acceleration due to gravity (m/s^2)
h	Heat transfer coefficient (kW/m^2K)
H	Opening height (m)
k	Thermal conductivity (kW/m K)

L	Total length of the two zones (m)
M	Interzonal mass flow rate (kg/s)
N	Air change rate (h^{-1})
Q	Heat transfer through the opening (kW)
S	Zone height (m)
t	Partition thickness (m)
T_1	Air temperature in zone 1 (^oC or K as specified)
T_2	Air temperature in zone 2 (^oC or K as specified)
ΔT	Temperature difference (^oC or K as specified)
U_R	Wind speed at a reference point (m/s)
V_c	Cross-ventilation rate (m^3/s)
V_s	Single-sided ventilation rate (m^3/s)
W	Opening width (m)
Pr	Prandtl number (dimensionless)
Gr	Grashof number (dimensionless)
Nu	Nusselt number (dimensionless)
Ra	Rayleigh number (dimensionless)
Re	Reynolds number (dimensionless)
β	Coefficient of thermal expansion (K^{-1})
ρ	Fluid density (kg/m^3)
$\Delta\rho$	Interzonal density difference (kg/m^3)
μ	Dynamic viscosity (N s/m^2)
υ	Kinematic viscosity (m^2/s)

INTRODUCTION

The study of airflow through large openings, eg, doorways in buildings, is important with regard to energy conservation and indoor air quality. For example, interzonal airflow plays an important role in the distribution of heat in passive-solar buildings and control of air movement is necessary in conventional buildings such as hospitals to prevent flow of contaminated air to other rooms. Interzonal airflow must also be taken into account when considering smoke and fire control in buildings. Air movement in buildings is an important phenomenum influencing draught, heat losses and condensation due to moisture flow from heated to unheated rooms. Interzonal airflow through doorways can occur as a result of natural convection caused by density differences, forced convection caused by mechanical ventilation, kinematic effects caused by occupant motion or a combination of these three.

Natural ventilation through large openings such as windows also has significant effects on energy conservation and thermal comfort. The characteristics of natural ventilation in buildings are dependent on the wind environment around the structure and the thermal gradient across the building envelope. Prediction of natural ventilation is difficult because of the involvement of a large number of variables and their complex interactions. For this reason most investigations have been carried out using scale models in wind tunnels.

Experimental and theoretical work has been carried out to study airflow through large openings and several airflow algorithms have been developed for computer programmes such as ESP[1], MULTIC[2], BREEZE[3], COMIS[4] and MOVECOMP[5]. These models are satisfactory when used to describe flow through simple crack or sharp-edge openings but improved algorithms are needed for more complex applications.

Anderson[6] and Barakat[7] have provided a limited review of research work into interzonal natural convection in buildings. The present paper provides an up to date review of work into airflow through large internal and external openings and outlines the requirements of future research necessary to develop improved algorithms.

REVIEW OF PREVIOUS WORK

In this section we review the most important work in the field of airflow through large openings. The first section describes airflow though internal openings and the second section describes airflow through external openings.

AIRFLOW THROUGH LARGE INTERNAL OPENINGS

Airflow in a two-zone building is shown in Figure 1. Air can infiltrate from outside the building into each zone (F_{01} and F_{02}) and exfiltrate from each zone to the outside (F_{10} and F_{20}). In addition air can exchange between the two zones in both directions through the opening (F_{12} and F_{21}). Assume that the two zones are tightly sealed (ie, F_{10}, F_{01}, F_{20} and $F_{02} = 0$) and the temperatures of zone 1 and 2 are T_1 and T_2, respectively. Using a theory based on the application of the Bernoulli equation, the volumetric flow rate through one half of the opening is:

$$F = (C_D\, W/3)\ \ (g\, H^3 \Delta T/T)^n \tag{1}$$

The theoretical value of n for a sharp-edged orifice is 0.5

The Nusselt number Nu, the Prandtl number Pr, Grashof number Gr, and Rayleigh number Ra, can be given by:

$$Nu_H = h\, H/k \tag{2}$$

$$Pr = c_p\, \mu/k \tag{3}$$

$$Gr_H = g\, \rho^2\, \beta\, H^3\, \Delta T/\mu^2 \tag{4}$$

$$Ra_H = Gr_H\, Pr \tag{5}$$

The relationship between Nu, C_D, Pr and Gr can be given by:

$$Nu_H = (C_D/3)\ Pr\ Gr_H^n \tag{6}$$

In the above equations the calculations of Nu, Gr and Ra are based on the characteristic length H. A review of previous research is as follows:

Several algorithms to describe airflow through internal large openings such as doorways have been developed. Brown and Solvason[8] have carried out experiments on heat and mass transfer occurring as a result of natural convection across openings in vertical partitions. The test unit used consisted of two large chambers 2.44m square, one of which was 1.22m deep and the other 4.27m deep. Tests were carried out for single rectangular openings of the following sizes 76.2mm x 76.2mm, 152.4mm x 152.4mm, 152.4mm x 304.8mm, 228.6mm x 228.6mm and 304.8mm x 304.8mm and air temperature differences ranging from 8.3 to 47.2°C. The temperature measurement grids were positioned 610mm from the opening in the direction parallel to the wall. The temperature on the warm side was maintained at about 40°C and experiments were carried out for a range of partition thickness to opening height, t/H. The experiments showed that for a given t/H ratio the exponent of the term Gr, given in equation (6) is always greater than 0.5. For Gr_H between 10^7 and 10^8 and t/H ranging from 0.19 to 0.38, the influence of t/H on Nu_H was found to be insignificant. For $Gr_H \leq 10^7$ and for t/H from 0.38 to 0.75, the influence of t/H on Nu_H was large.

Brown[9] also carried out experimental work on airflow occurring by natural convection through rectangular openings (152mm x 152mm, 228mm x 228mm and 305mm x 305mm) in horizontal partitions. Temperatures were measured at five locations 254mm from the opening. The experiments were conducted for Grashof numbers, based on the partition thickness, in the range 3×10^4 to 4×10^7 and for the ratio of partition thickness to the side of the square opening (ie, t/W) in the range 0.0825 to 0.66. The following correlation was obtained:

$$Nu_t = 0.0546\, Gr_t^{0.55}\, Pr\, (W/t)^{1/3} \qquad (7)$$

In another study, Brown et al[10] investigated heat and moisture transfer across openings in vertical and horizontal partitions separating spaces of different air conditions. Test results of natural convection through these openings produced the following equations:

For vertical partitions:

$$Nu_H = [1.16\, (1-0.6\, t/H)\, Gr_H^{0.432} - 215]\, Pr \qquad (8)$$

for $10^5 \leq Gr_H \leq 10^8$

$Nu_H = 0.343\ Gr_H^{0.5}\ (1 - 0.498\ t/H)\ Pr$ (9)

for $Gr_H > 6 \times 10^8$

For horizontal partitions:

$Nu_t = 0.0546\ Gr_t^{0.55}\ (t/W)^{1/3}\ Pr$ (10)

for $3 \times 10^4 < Gr_t < 4 \times 10^7$

Shaw[11] examined interzone airflow between two rooms occurring as a result of natural convection, and combined natural and forced convection. The experiments were carried out for openings 2.05m high and 0.1 to 0.9m wide. Interzonal temperature differences were in the order of 0-12°C and extract volumes were in the range 0-0.3 m^3/s. Air temperature and velocity in the doorway were measured using grids suspended from the top of each opening. The height of the opening and the temperature difference between the top and bottom of the opening were used to estimate Nu and Gr. The coefficient of discharge given in equation (1) was found to be dependent on the temperature differential and was defined by Shaw as the coefficient of temperature, C_T. The term C_T was found to be 0.65 for the temperature range 4 to 10°C and increased for temperature differentials lower than 4°C. The following equation was obtained for $10^6 \leq Gr_H \leq 10^{11}$:

$Nu_H = (C_T C_V/3)\ Gr^{0.5}\ P_r$ (11)

In a separate study, Shaw and Whyte[12] indicated that it is more practical to use the temperature difference between the centre of the two rooms in order to estimate interzone heat transfer. The value of the coefficient of temperature, C_T was found to be 0.8 (instead of 0.65 given in the previous study) for ΔT between 2 and 4°C. For $\Delta T >$ 4°C, C_T rose very slowly reaching a value of unity at about $\Delta T = 20$°C.

Measurement of heat transfer through doorways has been carried out by Wray and Weber[13], Weber et al[14] and Weber and Kearney[15] using a similarity model experiment and two buildings of different geometries. The scale model (S = 432mm, L =

1422mm, B = 737mm) contained Freon 12 refrigerant. Two methods were adopted to estimate the interzonal heat transfer and the following correlations were obtained.

$$Nu_H = 0.26\ Gr_H^{0.5}\ Pr \qquad (12)$$

Equation (12) was based on the difference between the average temperatures of the top and bottom halves of the doorway.

$$Nu_H = 0.3\ Gr_H^{0.5}\ Pr \qquad (13)$$

Equation (13) was based on the average of the weighted difference of the temperatures measured by thermocouples using grids located on the two sides of the doorway.

Nansteel and Grief[16, 17] performed experiments in a water-filled rectangular enclosure. Two cases were studied. In the first case, the partition was of constant height over the entire breadth of the enclosure resulting in a two-dimensional geometry. The enclosure had isothermal vertical sidewalls and insulated floor, ceiling and end-walls and had an aspect ratio, $H/L = \frac{1}{2}$. Experiments were carried out over the ranges, $3 \leq Pr \leq 4.5$ and $2.25 \times 10^{10} \leq Ra_L \leq 1.14 \times 10^{11}$. The following equations were obtained:

$$Nu_L = 0.748\ (H/S)^{0.256}\ Ra_L^{0.226} \qquad (14)$$

for a conducting partition, and

$$Nu_L = 0.762\ (H/S)^{0.473}\ Ra_L^{0.226} \qquad (15)$$

for a nonconducting partition

In the second case, the partition completely divided the enclosure except for a rectangular opening which allowed convection to occur across the enclosure. The vertical height of the opening (H) varied between S/4 and S and the opening breadth (W) was maintained at 0.093 B. Measurements of the cross-cavity heat transfer were carried out for the ranges, $3 \leq Pr \leq 4.3$ and $2.4 \times 10^{10} \leq Ra_L \leq 1.1 \times 10^{11}$ and the following equation was obtained:

$$Nu_L = 1.19\ (H/S)^{0.401}\ Ra_L^{0.207} \qquad (16)$$

A number of studies have been carried out at Los Alamos National Laboratory by Yamaguchi[18], Balcomb and Jones[19], White et al[20] and Jones et al[21] to investigate heat transfer occurring by natural convection in passive solar buildings. Yamaguchi investigated heat transfer through an aperture in a one-fifth similitude model of a two-zone building. The scale-model was filled with Freon-12 gas and tests were performed to study the effects of the height, width, and vertical position of the aperture on heat transfer. The results were generally consistent with work carried out by Brown and Solvason, Weber, and Grief and Nansteel. Balcomb and Jones presented the following simple equations which could be used by designers to estimate interzonal airflow and energy transport in buildings.

$$F = 0.0362\ W\ (H^3\ \Delta T)^{0.5} \tag{17}$$

$$Q = 0.0436\ W\ (H^3\ \Delta T^3)^{0.5} \tag{18}$$

Jones et al[21] have developed a mathematical model for heat and air transport in a two-zone building. The model included features which were derived from measurements carried out in more than 12 passive solar buildings. Measurements showed that for direct sun, the glazing is typically 5°C warmer than the sunspace air as a result of the solar absorption of the glass. This produces a strong upward boundary-layer flow over the glazing which entrains cool air from the sunspace core. Velocities of 0.46 to 0.61 m/s were measured in the glazing boundary layer. Jones et al indicated that the sunspace glazing accounts for more than half of the heat flow from the sunspace into the rest of the building during periods of strong solar heating. Results from the model were in general agreement with the measured data but improvements were needed to include the effects of heat transfer at horizontal surfaces such as floors and ceilings.

In 1987, Mahajan[22] measured interzonal heat and mass transfer in two full-sized adjoining rooms under two different conditions. Initially, one room was heated to an average temperature of 32°C, while the other room was cooled to an average temperature of 19°C. In the first test, the heating and cooling units were switched off the communication door was opened. In the second test, the cooling unit was switched off and the heating unit was left on. The temperature of the air was measured using temperature sensors installed in the rooms and at the top and bottom half of the doorway. The air speed was measured using hot wire anemometers and flow visualization was achieved using smoke generated by incense sticks. Results indicated that the rates of heat and mass transfer obeyed the following equations:

$$M = (0.45\ \rho/3)\ [g\ H^3/300]^{0.5}\ (\Delta T)^{0.5} \qquad (19)$$

$$Q = (0.45\ \rho c_p/3)\ [g\ H^3/300)]^{0.5}\ (\Delta T)^{1.5} \qquad (20)$$

Mahajan indicated that the value of C_D differed from values published by other researchers as a result of his specific experimental set-up and test conditions.

Reynolds[23], Reynolds et al[24] and Zohrabian et al[25] have carried out work on buoyancy driven flows of mass and energy in a half-scale model of a stairwell. The flow was three dimensional, unsteady and involved rapid mixing in the central region of the stairwell. The main feature of the flow was the presence of two interacting layers of hot upflow and cold downflow in the stairway along which heat and mass exchange took place. The total volume of the recirculating flow varied as $V \alpha Q^n$ where $n = 0.25$ for sloping-ceiling geometry, and $n = 0.22$ for non-sloping ceiling geometry.

Riffat[26] has investigated the heat and mass transfer through a doorway between the lower and upper floor of a house. The lower floor of the house was heated to various temperatures in the range 18-35°C using thermostatically controlled heaters. The upper floor was unheated. Temperatures were measured at the centre of the rooms and airflow rates were measured using two portable SF_6 systems. The coefficient of discharge was found to decrease from 0.61, at $\Delta T = 0.5°C$ to 0.22, at $\Delta T = 13°C$. The mass flow rate between the two zones was given by:

$$M = 0.0287\ \rho\ W\ (g\ H^3)^{0.5}\ (\Delta T/T)^{0.137} \qquad (21)$$

The relationship between Nu, Gr and Pr was:

$$Nu_H = 130.83\ Gr_H^{0.18}\ Pr \qquad (22)$$

Hill et al[27] investigated airflow due to natural convection in a full-sized passive solar building. A computer model was developed which predicated interzonal heat and mass transfer for stratified or isothermal temperature distribution in a zone. Good agreement was found between the experimental results and those predicted by the model. The coefficient of discharge, for the stratified model, was 0.75.

In 1988, Kirkpatrick and Hill[28] reported an experimental and theoretical study of interzonal natural and forced convection in a two and three-zone, passive solar building. The flow through the aperture was assumed to be quasi-steady and driven by the slowly varying zone pressure difference. Temperatures were measured using a vertical array of thermocouples positioned in the centre of the zones and doorway. Measurements of air velocity through the doorway were obtained using hot-wire aneometers. The coefficient of discharge was assumed to be 0.75. In the two-zone building the total mass flow rates through the doorway were 0.43 and 0.463kg/s at temperature differences of 5 and 8°C, respectively. In the three-zone building, the mass flow rates through the lower and upper doorways were 0.57 and 0.4 kg/s, respectively.

Scott et al[29] conducted an experimental study to determine the blockage of boundary layer flow due to natural convection in a multizone enclosure. The width of the aperture between the two zones was varied and measurements of heat transfer and temperature distributions were carried out. The experiment indicated that the boundary-layer flow required a smaller interzone temperature difference than a flow driven by bulk density difference provided that the area of the flow aperture was larger than 2% of the total cross-sectional area of the enclosure.

Tang et al[30] investigated heat transfer due to natural convection through an opening in a two-zone chamber with the dimensions of 5.5m x 2.5m x 2.5m. Experiments were performed for $4 \times 10^8 \leq Gr \leq 2 \times 10^9$. The temperatures of the wall surface and air in the two zones were measured using thermocouples. The coefficient of discharge was found to be in the range $0.42 \leq C_D \leq 0.45$ and the relationship between Nu, Pr and Gr was given by:

$$Nu_H = 1.225\ Gr_H^{0.4}\ Pr \qquad (23)$$

Equation (23) is based on the difference between the volume-weighted average temperatures.

Allard et al[31] carried out an experimental study on heat and mass transfer between two cells each of 3.1m x 1.1m x 2.5m. The interzone temperature difference was achieved by varying the temperature of the two opposite walls of the test chamber. For average interzone temperature differences of 30.5 and 25.5°C, the values of C_D were 0.73 and 0.77 (for isothermal rooms), and 0.85 and 0.88 (for uniform density gradients).

A few numerical studies of natural convection in enclosures have been reported [32-34]. Haghighat et al[35] used the k-ε, two-equation turbulence model to simulate natural convection of high Rayleigh number in a partitioned enclosure. The study concentrated on the effect of door height and location on the pattern of airflow and temperature. Results indicated that the flow pattern was sensitive to variations in door height and location, while the convection heat transfer rate was sensitive only to variations in door height.

AIRFLOW THROUGH LARGE EXTERNAL OPENINGS

This section summarises work which has been carried out to investigate airflow through external doorways and windows.

AIRFLOW THROUGH DOORWAYS

Buoyancy driven flow can occur as a result of a difference in fluid density across an exterior doorway. Figure 2a shows a diagram of an exterior opening with the interior fluid at T_i and density ρ_i and the exterior fluid at T_o and ρ_o. A review of previous work in this field is as follows:

Linden and Simpson[36] and Lane-Serff et al[37] investigated buoyancy driven flow through the transient period of the opening and closing cycle of a doorway. Data were obtained from small-scale laboratory experiments using salt and fresh water to model the buoyancy difference between the cold and warm air. They concluded that a doorway acts as a region of hydraulic control and after an initial acceleration phase, the flow takes on gravity current behaviour. The speed of fluid flow through the opening was:

$$U = 0.47\ (g\ H\ \Delta\rho/\rho)^{0.5} \qquad (24)$$

In 1986, Kiel and Wilson[38] carried out experimental work on airflow through an exterior doorway, with the dimensions 2.05m x 0.89m, in a full-scale room. The experiments were conducted for a range of indoor-outdoor temperature differences from 3 to 45^{o}C. Experiments were also performed using a 1:2 scale model with a salt water mixture to simulate indoor-outdoor temperature differences. The term, C_D was found to be equal to 0.6 for experiments performed using the scale model and the following equation was obtained from experiments performed in a full-scale room:

$$C_D = 0.4 + 0.0045\ \Delta T \qquad (25)$$

The authors indicated that the values of C_D were different for the scale model and full-scale room as a result of interfacial mixing across the doorway.

In a separate paper Keil and Wilson[39] presented data on pumping caused by the swinging motion of the door and buoyancy-driven couterflow caused by the temperature difference across the doorway. For typical swing speeds it was found that the pumping exchange could be neglected entirely when the temperature difference was in the range 3 - 5^{o}C. For a temperature difference of zero the volume pumped increased linearly with the speed of the moving door, with a typical exchange volume of about 50% of the swept volume of the door.

AIRFLOW THROUGH WINDOWS

Airflow through windows can be classified into the following types:

i) Single-Sided Ventilation

In this case, the airflow from a zone to remaining parts of the building is restricted compared with the flow between the zone and outside air. The airflow can occur through openings on one side of the zone only as shown in Figure 2a.

ii) Cross-Ventilation

In this case the spaces within the building are well-connected and airflow can occur through openings on opposite sides of an enclosure as shown in Figure 2b.

Previous work on airflow through large openings is described below:

Studies of natural ventilation using scale models have been carried out by Vickery[40], Krishnakumar et al[41], Aynsley[42, 43] Chandra[44] , Karakatsanis et al[45] and Liddament[46]. These investigations included the evaluation of airflow rates due to wind through large openings.

The ventilation rate, V_c was estimated using the discharge-coefficient method:

$$V_c = C_D A \left[(C_{P1} - C_{P2}) U_z^2\right]^{0.5} \qquad (26)$$

where C_{P1} and C_{P2} are the pressure coefficients on the windward and leeward surfaces of the model.

The discharge-coefficient method requires a detailed study of wind pressure distribution (ie, pressure coefficients) at many locations over the model surface.

de Gids and Phaff[47] estimated ventilation rate and energy consumption due to open windows. Measurements were carried out at three locations in a building situated in an urban environment. The air change rate per hour was:

$$N = (0.001\ U_R^2 + 0.0035\ H\ \Delta T + 0.01)^{0.5} \qquad (27)$$

In 1986, Warren[48] carried out work on measurements of single-sided ventilation in buildings. Results from tracer gas measurements indicated that the ventilation rate through a sliding window was given by:

$$V_s = 0.025\ A\ U_R \qquad (28)$$

where U_R is the design wind speed (in the undisturbed wind at the height of the building) obtained from standard meteorological data and A is the area of the window.

As part of the IEA-annex 8 "Inhabitants behaviour with regard to ventilation", Wouters et al[49] presented a number of 'rule of thumb' for estimating airflow rates through open windows. The following equation was given to estimate the volume flow rate through an open window due to single-sided ventilation.

$$V_s = (0.1 \text{ to } 0.25)\ A\ U_R \tag{29}$$

The 'rule of thumb' for cross-ventilation was:

$$V_c = (0.4 \text{ to } 0.8)\ A\ U_R \tag{30}$$

Etheridge and Nolan[50] studied ventilation rates in a scale model of a building in a wind tunnel. The model, containing either circular holes or window cracks, was a simple rectangular box 400mm x 210mm x 180mm. The model was tested (using tracer gas techniques) under two different angles to the wind direction. Tests indicated that flow through the circular holes becomes independent of Reynolds number for low wind speed, whereas the flow through the cracks is dependent on Reynolds number over the whole range tested. The ventilation rate was:

$$V_c = 0.65\ A\ U_R \sqrt{\Delta C_p} \tag{31}$$

Crommelin and Vrins[51] examined the ventilation rate through a single opening in a scale model. Airflow measurements were performed in a wind tunnel using a 0.3 x 0.3 x 0.3m^3 model. The ventilation rate (dm^3/s) for upstream lengths of 0.35 and 0.65m were:

$$V_s = 0.58\ U_R^{-0.64} \tag{32}$$

$$V_s = 0.58\ U_R^{-0.74} \tag{33}$$

The relationship between the ventilation rate (dm^3/s) and window size was:

$$V_s = 6.8\ A^{0.92} \tag{34}$$

Riffat[52] carried out measurement of window ventilation and interzone airflow in a scale model using tracer gas techniques. The model, which represented a two-storey house, had dimensions 0.85m x 0.85m. On the walls of each floor of the model, one inlet and one outlet opening with an area of 256mm^2 were made for ventilation. One additional large opening (area = 0.01 m^2) was made between the floors of the model to represent the stairway. The model was tested in a wind tunnel for wind speeds between 2.9 and 6.2 m/s. The cross ventilation rate was:

$$V_c = 2.084 \times 10^{-4} U_R^{1.15} \tag{35}$$

The average discharge coefficient for the window in the lower floor was found to be 0.56 and that for the upper floor was 0.62. The interzone airflow at a wind speed of 2.9 was 0.96 m^3/h.

In 1989, Van der Maas et al[53] compared the available algorithms for gravity-driven airflow through large openings with the requirements for multizone air-infiltration modelling. They addressed the problem of single-sided ventilation to a colder environment where flow is gravity-driven, not perturbed by wind, and in the absence of a heater. Experiments were carried out in scale models and a full-scale room. In the case of the scale model; $C_D = 0.5$ for ceiling - to - door height ratio = 1 and $C_D = 0.63$ for ceiling to - door height ratio > 1.5. For the full-scale model C_D was in the range 0.5 to 0.75.

In a separate study, Van der Mass et al[54] modelled transient single sided ventilation of a room taking into account the heat transfer between the air and walls. The ventilation rate expressed as a function of inside-outside temperature difference varies with time due to the cooling effect of the walls. Parameters used in the model were the room wall surface area and the thermal properties of the walls. The model allows an estimate to be made of heat loss through an open door and it was found that the heat loss dropped from 5kW to 50% of its value after 10 minutes, and decreased to 30% after 30 minutes.

Zainal and Croome[55] investigated the ventilation characteristics of a lecture room using various combinations of window-door openings. The ventilation rate was measured using the decay technique and CO_2 as the tracer gas. The ventilation rate of the room when windows were opened was given by:

$$N = 1.44 + 4.65\ A + 0.59\ U_L^2 - 0.013\ \theta - 0.023\ \Delta T \qquad (36)$$

The test results showed that the air change rate was strongly influenced by wind factors (ie, speed and direction) and window opening area. The effect of temperature difference was less significant.

RECOMMENDATIONS FOR FUTURE WORK

Further work is required to examine the validity of existing algorithms and also to determine the effects of incorporating other parameters into these equations. The following research topics require further investigation:

1. Examination of the effect on coefficient of discharge of the geometry of the zone and the aperture.
2. Experimental work to assist modelling of buoyancy-driven flow using similarity models and nondimensional parameters.
3. Determination of the effect on coefficient of discharge of interfacial mixing of air in doorways.
4. Examination of heat and mass transfer through large openings at low temperature differences (ie, below 1°C).
5. Examination of the blockage effect caused by occupant motion and furniture in a room.
6. Investigation of interzone heat and mass transfer through multiple doorways and stairwells.
7. Examination of the effect of temperature stratification and wall temperatures on the coefficient of discharge.
8. Examination of the effect of pressure due turbulence on the discharge and heat transfer coefficients.

9. Study of the combined wind and stack effect on single-sided ventilation using full-sized buildings.

CONCLUSIONS

Our literature survey showed that research studies have concentrated mainly on airflow through large openings in two-zone systems with simple geometrics. Airflow through openings was assumed to be one-dimensional and the blockage effect caused by furniture and people was neglected. The definition of interzonal temperature difference and experimental set-up were varied from one study to another resulting in different values of coefficient of discharge. The literature survey showed that little work has been carried out on heat and mass transfer through horizontal openings such as stairwells and staircases. The effects of pressure due turbulence, temperature stratification, wall temperature and interfacial mixing on the coefficient of discharge have for the most part been neglected. Only a few studies have been carried out on airflow through large openings under combined natural and forced convection. Study of airflow through windows, such as single-sided ventilation in real buildings has been limited.

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FIGURES

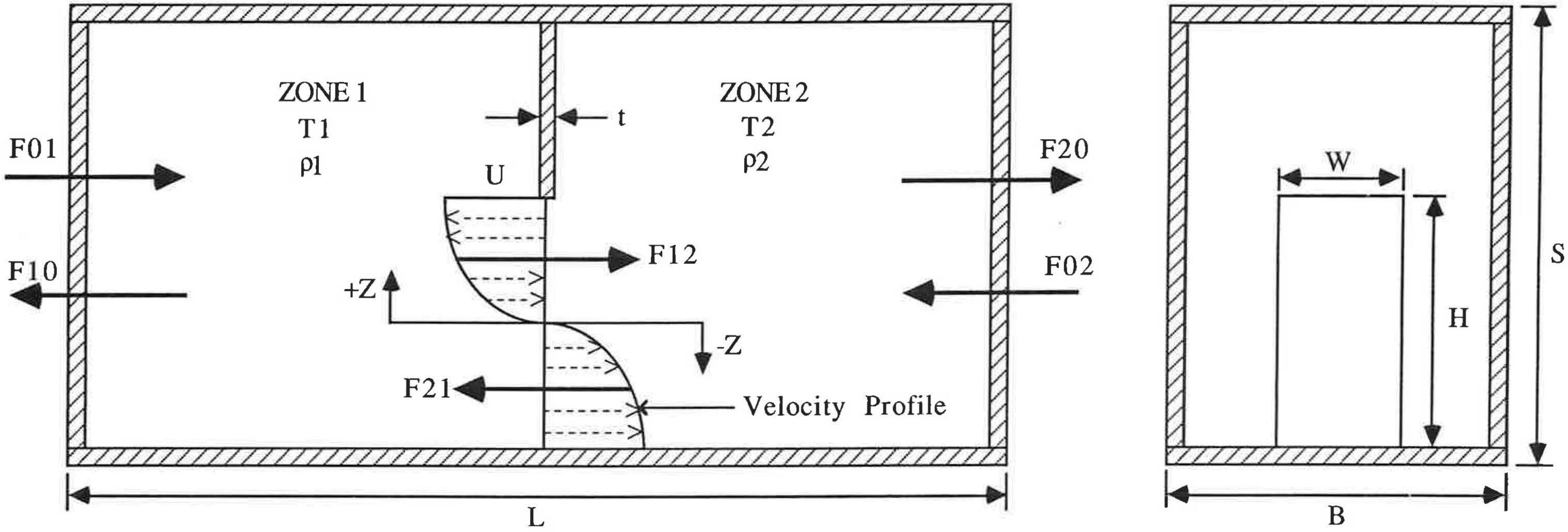
ZONE 1
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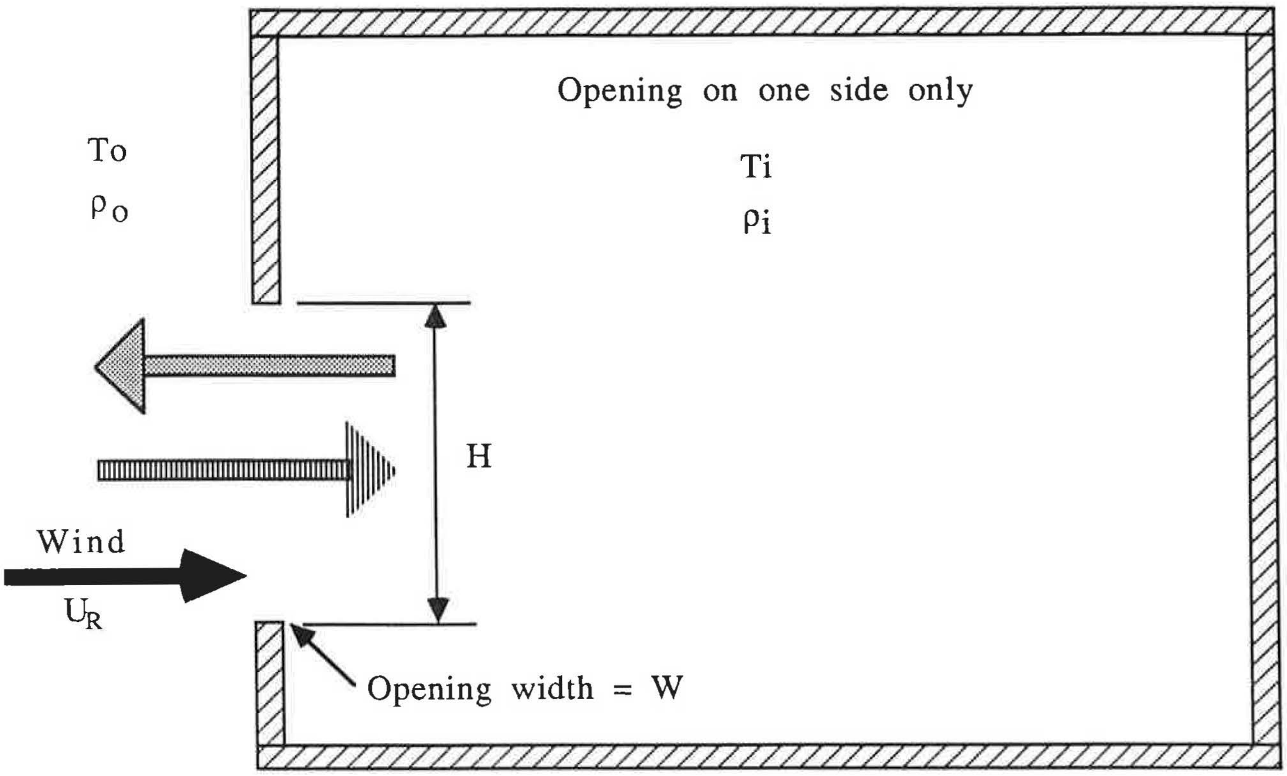
Fig. 1


Opening on one side only
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Wind
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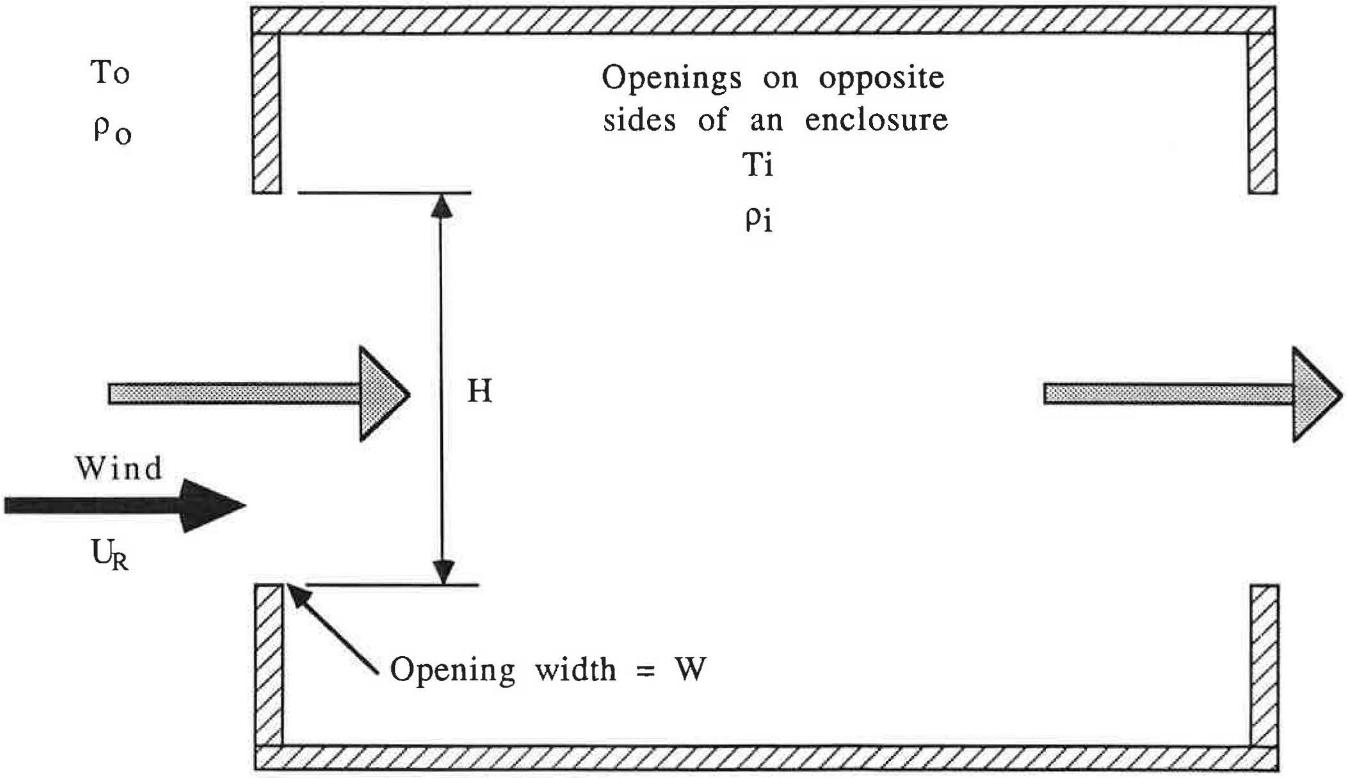
Opening width = W

Fig. 2a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Openings on opposite sides of an enclosure
Ti
ρi
H
Wind
UR
Opening width = W

Fig. 2b