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Infiltration Models for Multicellular Structures – A Literature Review

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SUMMARY

Infiltration models are used to simulate the rates of incoming and outgoing air flows for a building with known leakage under given weather and shielding conditions. Additional information about the flow paths and air-mass flows inside the building can only be made available by using multichamber infiltration models. Our review of the literature revealed the existence of 15 multichamber infiltration models, all developed between 1966 and 1983 and differing significantly in the number of cells they can handle, depending on the date of their development. In terms of the flow equations these programs use, they are very similar; most of the differences between them are in the description of the building and the algorithm provided for solving the set of nonlinear equations. In this literature review, we found that only a few of the 15 models are able to describe and simulate the ventilation system and the interrelation of mechanical and natural ventilation.

INTRODUCTION

The LBL infiltration model was developed in 1980 to simulate air infiltration of single-cell structures, such as single-family houses, under given weather conditions [1]. A high percentage of the existing buildings, however, have floor plans that characterize them more accurately as multichamber structures, which cannot be treated by single-cell models. This literature review is intended to be a first step in the development of a multichamber infiltration model.

The advantage of multichamber models, besides being able to simulate infiltration in larger buildings, is their ability to calculate mass flow interactions between the different zones. Knowing about the air-mass flow in buildings is important for several reasons, significant among them are that:

— exchange of outside air with the air inside the building is necessary for its ventilation;
— energy is consumed to heat or cool the incoming air to inside comfort temperature;
— air is needed for combustion and to exhaust gas for open fireplaces in different zones;
— airborne particles and germs are transported by air flow in buildings.
— air flow determines smoke distribution in case of fire.

The air-mass flow distribution for a given building is caused by pressure differences, whether evoked by wind, thermal buoyancy, mechanical ventilation systems or a combination of those. The distribution of openings in the building shell and the inner paths infuence the air flow too. The openings can be varied by the inhabitants, which can lead to significant differences in the pressure distribution inside the building. Figure 1 shows the influences on the air-mass flow distribution in detail.

In terms of air-mass flow, buildings are complicated interlacing systems of flow paths. In this grid system the joints are the rooms of the building and the connections between the joints simulate the flow paths and include the flow resistances caused by open or closed doors and windows or air leakage through the walls. The boundary conditions for the pressure can be described by the grid points outside the building. The wind pressure distribution depends on the velocity and the direction of the wind, the terrain surrounding the building, and the shape of the building. If the physical interrelationship between the flow resistance and the air flow is known for all flow paths, the air flow distribution for the building can be calculated, as long as there is no temperature difference between outside

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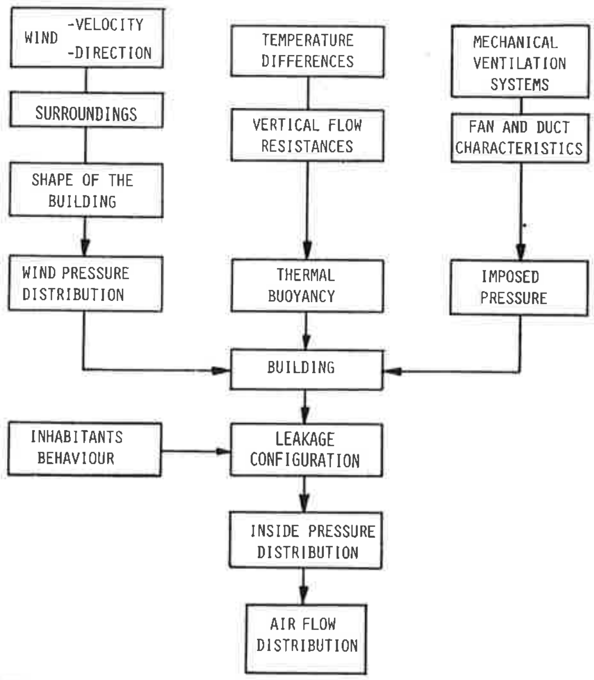

Fig. 1. Influences on the air-mass flow distribution.

and inside air. Differences in density of the air, due to differences between outside and inside air temperatures, cause further pressures in the vertical direction, again influencing the air-mass flow.

Mechanical ventilation can also be included in this network. The duct system can be treated like the other flow paths in the building. The advantage for calculating air flow distribution effects of mechanical ventilation systems is that the duct pathways, as well as their connections with the building, are known. In the case of mechanical ventilation systems the fan can be described as the source of pressure differences, lifting the pressure level between two joints according to the characteristic curve of the fan.

Because of the nonlinear dependency of the volume flow rate on the pressure difference, the pressure distribution for a building can be calculated only by using a method of iterations. To describe buildings with arbitrary floor plans and to solve the set of nonlinear equations, large computer storage is necessary.

LITERATURE REVIEW

The Air Infiltration Centre (AIC) has recently published a review of ten mathematical infiltration models [2] that have been developed in five of the AIC participating countries. Only five of those described are multichamber infiltration models. The additional ten multichamber models described in this report show the necessity of a extended search. A literature survey produced 26 papers describing 15 different models developed in eight countries. In addition to the scarcity of computer programs for modelling infiltration in multicellular structures the descriptions of existing programs were not adequate for our purposes. Accordingly we developed a questionnaire and mailed it to all program authors, and completed one for our own model as well.

In cases where the questionnaire was not returned, we answered the questions ourselves by using the reviewed literature. If, in these cases, the reviewed papers did not give us a reasonable answer to a certain problem, we entered a question mark in the questionnaire.

The completed questionnaires are reproduced below. The addresses shown are the current addresses of the authors, rather than the addresses of the institution where the program was developed. Equations and references are reproduced separately in Appendix 1.

Questionnaires received from authors of computer programs

Name and address: D. W. Etheridge,
British Gas Corporation,
Watson House,
Peterborough Road,
London SW6 3HN,
United Kingdom.

References: 3 - 6

Equation used for		
— flow through cracks:	1 (D)	
— flow trough large openings:	2 (D)	
— flow through duct work:	—	
— fan flow characteristics:	constant	
— wind pressure:	5 (C)	
— thermal buoyancy:	6 (B)	
— outside pressure fluctuation:	7 (A)	
— circulation flow on large openings:	—	
Algorithm to solve the nonlinear set of equations		
— name of algorithm:	Internal reference pressure adjusted until flow errors negligible	
— equation:	?	
	VENT 1	VENT 2
Maximal number of rooms: (including shafts, corridors, etc.)	40	2
Limits on number of		
— openings per room:	no limits per room	40
— shafts, corridors, floors:	40/40/40	0
— mechanical ventilation systems:	one flow per opening	1
Program language:	FORTRAN 77	BASIC
Program available:	limited availability	limited availability
Written for computer type:	HARRIS and CAI ALPHA	TEKTRONIK 40/5 HP 87

Name and address: P. R. Warren and M. D. A. E. S. Perera,
Building Research Establishment,
Bucknalls Lane,
Garston, Watford WD2 7JR,
United Kingdom.

References: 7

Equation used for	
— flow through cracks:	1 (H)
— flow through large openings:	2 (D)
— flow through duct work:	3 (D)
— fan flow characteristics:	4 (D)
— wind pressure:	5 (B)
— thermal buoyancy:	6 (F)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	BREEZE
— equation:	Iterative technique using linear approximation to a set of nonlinear equations including Q and P
Maximal number of rooms: (including shafts, corridors, etc.)	60
Limits on number of	
— openings per room:	not restricted; one cell can be jointed to another by only one flow path
— shafts, corridors, floors:	max. no. of rooms; 10 floors
— mechanical ventilation systems:	no restriction except that they conform to an overall size restriction of 60 zones
Program language:	FORTRAN 77
Program available:	Yes, but not user-friendly
Written for computer type:	VAX; it also has been implemented on TEL 1904S

Name and address: P. J. Jackman,
Building Services Research and Information Association,
Old Bracknell Lane West,
Bracknell, Berkshire RG12 4AH,
United Kingdom.

References: 8, 9

Equation used for	
— flow through cracks:	1 (C)
— flow through large openings:	2 (C)
— flow through duct work:	not applicable
— fan flow characteristics:	not applicable
— wind pressure:	5 (B)
— thermal buoyancy:	6 (C)
— outside pressure fluctuation:	not applicable
— circulation flow on large openings:	not applicable
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	Hardy Cross to establish reasonable first estimate followed by Cholesky triangular factorization
— equation:	8 (C)
Maximal number of rooms: (including shafts, corridors, etc.)	limited by available computer memory size
Limits on number of	
— openings per room:	no particular limit
— shafts, corridors, floors:	no particular limit
— mechanical ventilation systems:	no particular limit; mechanical ventilation is simulated as specified air flow rate per room
Program language:	FORTRAN
Program available:	for use by BSRIA staff only
Written for computer type:	PRIME 300

Name and address: J. Gabrielsson,
Ekono Association for Power and Fuel Economy,
P.O. Box 27,
00131 Helsinki 13,
Finland.

References: 10

Equation used for	
— flow through cracks:	1 (G)
— flow through large openings:	—
— flow through duct work:	3 (A)
— fan flow characteristics:	interpolated from fan curve
— wind pressure:	5 (E)
— thermal buoyancy:	6 (B)
— outside pressure fluctuation:	as in ASHRAE procedure for determining heating and cooling loads for computerized energy calculations. Algorithms for building's heat transfer subroutines, New York 1971
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	—
— equation:	8 (A)
Maximal number of rooms: (including shafts, corridors, etc.)	725
Limits on number of	
— openings per room:	unlimited
— shafts, corridors, floors:	5; 720; 720
— mechanical ventilation systems:	20

Program language:	FORTRAN 77
Program available:	limited (Finnish manuals only)
Written for computer type:	VAX 11/780

Name and address: C. Y. Shaw,
Bldg. M-24 Division of Building Research,
NRC, Montreal Road,
Ottawa KIA OR6,
Canada.

References: 11 - 13

Equation used for	
— flow through cracks:	1 (F)
— flow through large openings:	2 (E)
— flow through duct work:	constant
— fan flow characteristics:	—
— wind pressure:	cp (wind tunnel measurements)
— thermal buoyancy:	6 (D)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	CP 45
— equation:	8 (D)
Maximal number of rooms: (including shafts, corridors, etc.)	25 components and 8 shafts
Limits on number of	
— openings per room:	4
— shafts, corridors, floors:	1
— mechanical ventilation systems:	up to 8
Program language:	FORTRAN IV
Program available:	yes
Written for computer type:	IBM 360

Name and address: G. N. Walton,
National Bureau of Standards,
BR/B114,
Washington DC 20234,
United States of America.

References: 14

Equation used for	
— flow through cracks:	1 (A)
— flow through large openings:	2 (A)
— flow through duct work:	—
— fan flow characteristics:	—
— wind pressure:	5 (A)
— thermal buoyancy:	6 (A)
— outside pressure fluctuation:	user input
— circulation flow on large openings:	by multiple large openings
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	Newton (modified)
— equation:	8 (E)
Maximal number of rooms: (including shafts, corridors, etc.)	it is intended that the program be compiled with the appropriate values of a few parameter statements to match the program to the problem
Limits on number of	
— openings per room:	
— shafts, corridors, floors:	
— mechanical ventilation systems:	

Program language:	FORTRAN 77
Program available:	yes
Written for computer type:	SPERRY 1100 (also running on VAX and IBM)

Name and address: S. J. Irving,
The Oscar Fabership Marlborough House,
Upper Marlborough Road,
St. Albans, Herts. AL1 3UT,
United Kingdom.

References: 15, 16

Equation used for	
— flow through cracks:	1 (B)
— flow through large openings:	2 (B)
— flow through duct work:	—
— fan flow characteristics:	4 (A)
— wind pressure:	5 (B)
— thermal buoyancy:	6 (B)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	Newton-Raphson
— equation:	8 (B)
Maximal number of rooms: (including shafts, corridors, etc.)	300
Limits on number of	
— openings per room:	120
— shafts, corridors, floors:	no limits within the above constraints
— mechanical ventilation systems:	
Program language:	FORTRAN IV
Program available:	limited availability
Written for computer type:	PRIME 50 series machine

Name and address: Ch. F. Pedersen,
Statens Byggeforskningsinstitut,
Postbok 113,
DK-2970 Horsholm,
Denmark.

References: 17

Equation used for	
— flow through cracks:	1 (I)
— flow through large openings:	?
— flow through duct work:	?
— fan flow characteristics:	?
— wind pressure:	?
— thermal buoyancy:	?
— outside pressure fluctuation:	?
— circulation flow on large openings	?
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	nodes and loops à la Kirchhoff
— equation:	?
Maximal number of rooms: (including shafts, corridors, etc.)	100
Limits on number of	
— openings per room:	?
— shafts, corridors, floors:	?
— mechanical ventilation systems:	?

Program language:	?
Program available:	?
Written for computer type:	?

Name and address: W. F. deGids,
Institute for Environmental Hygiene — TNO,
P.O. Box 214,
NE-2600 AE Delft,
Netherlands.

References: 18

Equation used for	
— flow through cracks:	1 (E)
— flow through large openings:	2 (F)
— flow through duct work:	3 (E)
— fan flow characteristics:	4 (E)
— wind pressure:	5 (B)
— thermal buoyancy:	6 (G)
— outside pressure fluctuation:	7 (B)
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	K-Newton
— equation:	8 (D)
Maximal number of rooms: (including shafts, corridors, etc.)	50
Limits on number of	
— openings per room:	total number of connections smaller than 200
— shafts, corridors, floors:	
— mechanical ventilation systems:	
Program language:	HPL
Program available:	no
Written for computer type:	HP 9825/HP 9816

Name and address: W. Brinkmann,
Bundesbaudirektion Berlin,
Fasanenstrasse 87,
D-1000 Berlin 12,
Federal Republic of Germany.

References: 19

Equation used for	
— flow through cracks:	1 (E)
— flow through large openings:	—
— flow through duct work:	—
— fan flow characteristics:	—
— wind pressure:	5 (D)
— thermal buoyancy:	6 (B)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	—
— equation:	the exact nonlinear equations were solved to determine the volume flow rate: the balance of in- and outflowing air was determined by iteration (variation of the neutral pressure level NPL)
Maximal number of rooms: (including shafts, corridors, etc.)	in horizontal direction (per floor) 3 groups of rooms; outside group divided in windward and leeward flats, inner

	group (shafts), middle group (corridors) combine the different groups: in vertical direction; 30
Limits on number of	
— openings per room:	one to each attached region
— shafts, corridors, floors:	unlimited; one per floor; 30
— mechanical ventilation systems:	no mechanical ventilation
Program language:	HP-Special
Program available:	only in parts
Written for computer type:	HP

Name and address: H. E. Feustel,
Lawrence Berkeley Laboratory,
Building 90, Room 3074,
Berkeley, CA 94720,
United States of America.

References: 20, 21

Equation used for	
— flow through cracks:	1 (E)
— flow through large openings:	—
— flow through duct work:	3 (B)
— fan flow characteristics:	4 (B)
— wind pressure:	5 (D)
— thermal buoyancy:	6 (B)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	Newton
— equation:	8 (B)
Maximal number of rooms: (including shafts, corridors, etc.)	200
Limits on number of	
— openings per room:	unlimited
— shafts, corridors, floors:	no limit within the above constraints
— mechanical ventilation systems:	6
Program language:	FORTRAN IV
Program available:	no
Written for computer type:	CDC CYBER

Name and address: G. Hausladen,
Schiedel GmbH & Co.,
Lerchenstrasse 9,
Postfach 50 05 65,
D-8000 Munich 50,
Federal Republic of Germany.

References: 22 - 24

Equation used for	
— flow through cracks:	1 (E)
— flow through large openings:	—
— flow through duct work:	3 (C)
— fan flow characteristics:	4 (C)
— wind pressure:	5 (B)
— thermal buoyancy:	6 (E)
— outside pressure fluctuation:	—
— circulation flow on large openings:	—

Algorithm to solve the nonlinear set of equations
— name of algorithm: ?
— equation: ?

Maximal number of rooms: ?
(including shafts, corridors, etc.)
Limits on number of
— openings per room: 4
— shafts, corridors, floors: 1; 0; ?
— mechanical ventilation systems: ?

Program language: ?
Program available: ?
Written for computer type: ?

Name and address: J. P. Cockroft,
Building Services Research Unit,
University of Glasgow,
3 Lillybank Gardens,
Glasgow G12 8RZ,
United Kingdom.

References: 25, 26

Equation used for
— flow through cracks: 1 (E)
— flow through large openings: not specified
— flow through duct work: ?
— fan flow characteristics: ?
— wind pressure: ?
— thermal buoyancy: ?
— outside pressure fluctuation: ?
— circulation flow on large openings: not specified

Algorithm to solve the nonlinear set of equations
— name of algorithm: ?
— equation: ?

Maximal number of rooms: ?
(including shafts, corridors, etc.)
Limits on number of
— openings per room: ?
— shafts, corridors, floors: ?
— mechanical ventilation systems: ?

Program language: ?
Program available: ?
Written for computer type: ?

Name and address: R. E. Bilsborrow,
Department of Building Science,
Faculty of the Architectural Studies,
University of Sheffield,
Sheffield S10 2TN,
United Kingdom.

References: 27, 28

Equation used for
— flow through cracks: 1 (E)
— flow through large openings: ?
— flow through duct work: ?
— fan flow characteristics: ?
— wind pressure: ?

— thermal buoyancy:	?
— outside pressure fluctuation:	?
— circulation flow on large openings:	?
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	?
— equation:	?
Maximal number of rooms: (including shafts, corridors, etc.)	211
Limits on number of	
— openings per room:	4
— shafts, corridors, floors:	1; ?; 10
— mechanical ventilation systems:	?
Program language:	FORTRAN
Program available:	yes
Written for computer type:	ICL 1907

Name and address:	K. S. Swetlov, Soviet Union.
References:	29

Equation used for	
— flow through cracks:	1 (D)
— flow through large openings:	2 (G)
— flow through duct work:	2 (G)
— fan flow characteristics:	?
— wind pressure:	?
— thermal buoyancy:	?
— outside pressure fluctuation:	?
— circulation flow on large openings:	?
Algorithm to solve the nonlinear set of equations	
— name of algorithm:	Newton
— equation:	?
Maximal number of rooms: (including shafts, corridors, etc.)	150
Limits on number of	
— openings per room:	?
— shafts, corridors, floors:	?
— mechanical ventilation systems:	?
Program language:	?
Program available:	?
Written for computer type:	?

DISCUSSION

Whereas single-cell models are somewhat more variable in their performance [2], the investigated multichamber models were, with regard to the equations used, very similar to each other. The flow equation used to describe the air flow characteristics of the buildings is similar to the one describing measured results for air flow through building components [30 - 36]. Twelve of the 15 programs use this empirical power-law expression type of equation; even though the pressure exponent may differ from 0.5 to 1.0, depending on the nature of flow. A comparison of air leakage measurements conducted in 196 houses by means of the blower door technique showed, for the whole house, a mean value for the exponent of 0.66 [37], which is in good agreement with the measured flow characteristics of building components.

A second commonality among program authors (six of the fifteen) was their use of Newton's method of iteration for solving the set of nonlinear equations. However, the method of solving this problem varied from simple one-dimensional methods [23] to the two-dimensional methods described above. The differences are seen in the necessary storage and the quality of convergence.

Unfortunately, the programs reviewed here have one negative point in common: most of them are available only to a limited number of users.

The programs differ most in their ability to simulate mechanical ventilation systems. Eight of them are not able to simulate forced ventilation at all, or at least the references do not indicate any handling of ventilation systems; two use the simplified method of setting a fixed air-mass flow for unbalanced mechanical ventilation systems, and only five describe mechanical ventilation systems by means of fan and duct characteristics. The latter are able to simulate the interaction of mechanical and natural ventilation.

The difficulties of measuring infiltration in multichamber structures means that few such models have been validated properly, if at all. The possibility of doing piecemeal validations of certain algorithms has been considered; e.g. the algorithms for air flow through open doorways or air flow through cracks have been tested separately [38]. Even though infiltration cannot be measured for an entire building at once, measuring a few cells of the whole structure could still provide a severe test for existing models.

These data are important not only for validation purposes but also as a means of further understanding of air movement in large multizoned buildings. We need to identify the critical variables in different building types in order to develop more accurate input data, and ultimately, more accurate models. Wind pressure coefficients, for example, represent a factor that needs further study, and collating of existing data should help our efforts to simplify data requirements.

CONCLUSION

Multichamber infiltration models treat the true complexity of flows in a building in recognizing effects of internal flow restrictions. They require extensive information about flow characteristics and pressure distributions, and, in many cases, are too complex to justify their use to predict flow for simple structures, such as single-family residences [39].

Most multicellular models presently in use are not available to the public or are written as research tools, rather than for the use of professional engineers or architects. There is an obvious need for a simplified multichamber infiltration model capable of providing the same accuracy as the established single-cell models.

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APPENDIX 1

List of symbols

A	area	m^2
B	constant	—
C	crack flow coefficient	$m^3/m\ h\ Pa^n$
CR	correction term	Pa
D	flow coefficient	$m^3/h\ Pa^n$
E	effective leakage area	cm^2
F	mass flow rate	kg/h
H	height	m
K	constant	—
L	crack length	m
N	number of storeys	
P	pressure	Pa
Q	volume flow rate	m^3/h
S	resistance	$h\ Pa/m^3$
T	temperature	K
X	considered storey	
a, b, c	coefficients	—
c_p	surface pressure coefficient	—
f	function of	—
g	gravity	m/s^2
i, m	number of ductwork components	—
n	flow exponent	—
t	temperature	°C
v	wind speed	m/s
z	depth of crack	m
ρ	air density	kg/m^3
μ	viscosity of air	m^2/s
λ	friction factor	—
ξ	fitting loss coefficient	—
θ	absolute temperature	K

Subscripts

o	outside
f, i, r, s	locations in the duct system
i	inside
j	iteration step
$j+1$	iteration step + 1
s	stack
v	velocity
0	reference
NET	inside

TABLE 1

Equations used for flow through cracks

1 (A)	$F = D \times \Delta P^n$
1 (B)	$Q = D \times \Delta P^n$
1 (C)	$\frac{Q}{3600} = \frac{D}{3600} \times \Delta P^{1/n}$
1 (D)	$\Delta P = a \times Q^2 + b \times Q$
1 (E)	$Q = C \times L \times \Delta P^n$
1 (F)	$F = K \times \Delta P^x$
1 (G)	$Q = C \times A \times \Delta P^n$
1 (H)	$\Delta P = \left(\frac{Q}{K \times L}\right)^n$
1 (I)	$\Delta P = 0.5 \times L \times \rho \times Q^2$

TABLE 2

Equations used for flow through large openings

2 (A)	$F = D \times \Delta P^n$
2 (B)	$Q = D \times \Delta P^n$
2 (C)	$\frac{Q}{3600} = \frac{D}{3600} \times \Delta P^{1/n}$
2 (D)	$Q = A \times C \times \left(\frac{2\ \Delta P}{\rho}\right)^{1/2}$
2 (E)	$F = K \times \Delta P^x$
2 (F)	$Q = A \times (2\ \Delta P)^{1/n} \times (1/\rho)^{1/2}$
2 (G)	$\Delta P = S \times Q^2$