CASE STUDIES IN AIR INFILTRATION MODELLING

A paper presented to the BEPAC Air Movement Task Group at its meeting on 1st May 1990, British Gas Midland Research Station, Birmingham. Note that this is a preliminary paper, not the final version.

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SUMMARY

This paper introduces the concept of nodal network air flow modelling in buildings. Four case studies involving air infiltration modelling are then described. These case studies have been selected from a portfolio of computer modelling projects carried out by the author whilst working for the Energy Design Advisory Service (EDAS), a government funded scheme offering energy advice to Scottish building designers, and operated through the Royal Incorporation of Architects in Scotland (RIAS).

NODAL NETWORK AIR FLOW MODELLING

A number of nodal network air flow models (sometimes termed 'zone' models) exist for predicting building air infiltration and internal zone coupled air movement. Such models, typically, calculate air flow in some air leakage network as caused by mechanical supply/extract systems, external wind pressure or temperature differences.

This paper is concerned with the practical application of the mfs (mass flow solver) general fluid flow simulation model to the problem of predicting air movement in buildings. The mfs model, developed collaboratively between ESRU, University of Strathclyde and FAGO, Eindhoven University of Technology, is a stand-alone package which can be used not only for air movement prediction, but also for modelling of other fluid networks, e.g. water circuits, etc. The package may also be run in tandem with the ESP dynamic building thermal simulation program when buoyancy effects are considered important, necessitating calculation of time varying zone air temperatures.

Generating a network model

The first step in nodal network air flow modelling is creation of

an air leakage network such as the one shown in Figure 1. This contains a description of nodes (or zones) within and outwith the building and identification of all leakage paths or connections between zones through which air can flow.

Nodes may be internal or external. An internal node represents either a volume of air within the building (a zone or part of a zone), or a mechanical supply/extract point. Fixed temperatures are assigned to each node and, when buoyancy effects are to be taken into account, height differences between nodes may be specified. An external node represents an 'outside' boundary to the network. At an external node, wind pressure is calculated as a function of wind speed & direction and surface pressure coefficient. Temperatures at external nodes are taken from the climate file which contains hourly values of the various climate parameters.

To complete the network, nodes are connected together by an appropriate fluid flow component type. Currently supported component types are given in Table 1. The component types of particular interest for air flow modelling purposes are numbers 30 (to define a mechanical supply/extract), 110, 120 and 130.

In the case of external nodes, an appropriate pressure coefficients data set has to be specified. A standard pressure coefficients file exists which holds values of external surface pressure coefficient for 16 compass directions, i.e every 22.5 degrees. The file currently comprises 29 coefficient sets. Table 2 describes each coefficient set in terms of surface aspect, dimensions and exposure. The first 27 sets are taken from a publication of the TEA's Air Infiltration and Ventilation Centre (Air Infiltration Techniques - An Applications Guide). These sets can be used (with care) for low rise buildings (up to 3 storeys).

Simulating air flow in the network

When the air leakage network has been generated, a steady state simulation can be performed against any climate data set which contains weather information in the appropriate format. The simulation technique of mfs is to assign an arbitrary pressure to each of the nodes participating in the network. The flow along each connecting branch, representing the cracks, area openings and doorways, is then determined from empirical equations which relate air flow to pressure difference. A special algorithm within mfs is designed to iteratively adjust nodal pressures until the air mass balance at each node is below some specified residual vale. To aid the numerical solver, a number of convergence devices are made available for use in the case of complex leakage schemes involving a mix of large and small flowpaths.

Simulation results can be displayed in tabular or graphical format.

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Zone 10: loft en a martinezza a com 1121 - 3 1071 45 S.C. 3. 4. E was the st stall in the set 11 In 1980 5 23 1.0 1 4 15.15 31.142 Zone 6: bedroom 2 Zone 9: W.C. 21 M 14 . V. 121 Zone 8: bathroum 19. cm 243 10 - Zone 5: bearoom 1' / 10 Zone 11: Landing 1117 I at 10 18 1. 5. 2. 2. 2. £. 1. Zone 7: bedroom T **** *** 17 E 1 н^{а — 21} 22 12 17.19 17 12 15 80 17. 1 13 - 4 " M 3 F. . . 50% 3 Zone 2: dining room 1 42 . 2.2 . 2 . 1. D 20 2 M 20 Zone 3: kitchen : 210 ÷. - Zone J: living.doom 2 T. 50 1. Zone 4: hall 2013 A 3 . 197 Figure 2: Zoning strategy. + Y = 1033 Sec. Oak PLOT S ABACUS : VIEWER 6 5 tic autom . L² 1° ¢. 5913 1119 $\gamma = \gamma \gamma r_{1}$ B1 A. SMLT. figure 1 a : 10 zone ESP domestic house model. Shown exploded. in in 1 2, 62 1 2 1 5 . 7 . . E. $\varphi = \frac{1}{1} \left[1 - \frac{1}{2} \right]^{2 - 1}$ 4.1 *** ****) <u>;;</u>-2.2 roof 5.1 11. 302. 1.31 - 41 to - 18 -. 21 C. A. M. 1988 a my i phy ang i . S E. 1.700 1.15 .1 5 f 1 1 general' léakage 5 (north) 9 11 1 1 4.1 north north (zone 10) 1 15 3 1 the lot of the second of 34.3 windfie 1 12. -1 wandow! STL CLASS AND LEP 142.4 1º States States zone (200# 5) ster rody factors 22.00 bath 981 hatch . (877 5.7 i ci mi z: 3. The Model of the Lord of the 5757 TE X TO YET 结门关键 磁磁路 口台运行中于 12 1 . The " 1 Seat 1 9: (zone 5) bed 1) durch as right and ALS TOTA C in (zone1)E STT IN A POLICE "f ± land window 54 elor Car Carlo 1217 ali washi yangida s angi washi yangida 112 - S 341 5 - -Car Coor мтцерая zone 7 3 JE ST bed 2 - galse a a control of St 20 13 12113 1-893 (south) 20 the dest - r c dil. of involution individual training -indow 100 C NATE L'UCE (L. L'ESC, no. all doord and sundown are closed SENICAL 7 (L'ENCET) Juis of provise ANN 17 Juis of provise 1.1.1.5 . 1.15 1. SQ . C # 11 north south f (1 (B) 8) 100002 23.0 1 totathers suce no sex 11 (b) (c) (c) 410 wind E_{2}^{*} * 541 TO DE TEL TEL TEL DES. SO SER SEÀ DE TEL TEL DE DES. SO SER SEÀ DE TEL DE DE TEL DE DE TEL DE まんご 2352.2 6. WPS& 85.17 1 81 - 1 N.T. - 51 kit north 251 3 1 . C partially of ÷ · 12 * $-\hat{X}^{\dagger} = -\hat{X}^{\dagger}$ door 10 partially of zone 2 (zone 4 hall) 1.50 B B P BLEET F. - - - din. 1.2 1.00 zone 1 liv. outh

Figure 1 b : Air leakage distribution network for 10 zone house model.

type	description	"formula"	supplementary data ⁽¹⁾
10	Power law volume flow resistance element	$\dot{m} = \rho a \Delta P^b$	2. coefficient a
	the law and the		3. exponent b
15	Power law mass flow resistance element	$\dot{m} = a \Delta P^{b}$	2. coefficient a
			3. exponent b
17	Power law mass flow resistance element.	$\dot{m} = a \sqrt{\rho} \Delta P^{b}$	2. coefficient G
	at had the	1. W. S. S.	3. exponent b
		m m a	307 3* 5: Tr
20	Quadratic law volume flow resistance eleme	ant $\Delta P = a - b (\frac{1}{2})^2$	2. coefficient a
		P P	3. coefficient b
25	Quadratic law mass flow resistance element	$\Delta P = a \dot{m} + b \dot{m}^2$	2 coefficient ()
1000			3. coefficient b
30	Constant volume flow rate element	$\dot{m} = \rho a$	2. volume flow rate a
35	Constant mass flow rate element	$\dot{m} = a$	2. mass flow rate a
40	Common orifice flow element	$\dot{m} = o f (Cd A o \Delta P)$	2. opening area A
	and the second		3. discharge factor Cd
50	Laminar pipe flow element	$\dot{m} = \rho f (L R \sqcup \Delta P)$	2. length of flow path L
		1	3. radius of opening R
110	Air flow opening ⁽²⁾	$\dot{m} = o f (A \Delta P)$	2. area A
120	Ais flow smak	$\dot{\mathbf{m}} = \alpha f(W I \Lambda P)$	2 and width W
120	All now crick	m = p f (m D dz)	3. crack length L
130	Ais flow door	$\vec{m} = 0 f(W H H C A)$	P) 20 2 done with W
150	1 100 CON	and the first	3. door height H
	10 - 24	· 1/ / 1/3	4. reference height $Hr_{(4)}^{(5)}$
	LAPC RIVER ST.	and the second	5. discharge factor Cd
210	General flow conduit (duct or pipe)	$\dot{m} = \rho f (D_h A L k \Sigma C_i)$	$V \Delta P$) 2. hydraulic diameter D_h
	, the En P L	1. 14 × 11	3. cross-sectional area A
	÷ .	25 ×31 1, 1493	4. conduit length L
	1.22 - 32 - ²	att t < ta	5. wall roughness /
	1.8 32	i. a	loss factors ΣC :
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220	General flow inducer	$\Delta P = a_0 + a_1 \frac{m}{n} + a_2($	$\frac{m}{m}$) ² 2. min. volume flow rate \dot{q}_{min}
	Leaves .	rati Carta	P 3. max. volume flow rate a
	· K73 4	1 M	135 . 4
	I Thinks	$q_{\min} \ge \rho \ge q_{\max}$	tu A coerneite ao
	-26	· ,	5. coefficient a1
		AND THE TOTAL STREET	o. coefficient d2.
230	General flow junction ⁽³⁾	14 Mar 14	
240	General flow corrector		
(1)	first supplementary data item is always fluid	type (1 = air, 2 = water)	
(2)	identical to type 40 with $Cd = 0.65$ [-]		
(3)	implicit in mfs: $Hr = 1.50 [m]$		
(4)	implicit in mis: $Cu = 0.92$		

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TABLE	1	:	Currently	Supported	F]uid	Flow	Component	Types
			in mfs.					

	Database Reference	Facade Description	Length to width Ratio	Exposure		
	1	Wall	1:1	Exposed	10% C	(¥)
	3 2c He	Roof, pitch > 10 deg	1:1	Exposed		
	3	Roof, pitch 10-30 deg	s 1:1 -	Exposed	" "Enchi	
	4 Most	Roof, pitch > 30 deg	1:1	Exposed	1.1.1.1.1.1.1	
	5.	Wall	1:1	Semi-Exposed		
	6	Roof, pitch < 10 deg	1:1	Semi-Exposed		Se
	7	Roof, pitch 10-30 deg	1:1	Semi-Exposed	1	81.0
	· 87.50	Roof, pitch > 30 deg	1:1	Semi-Exposed		2.2.
	9	Wall	1:1	Sheltered	1	
	10	Roof, pitch < 10 deg	· 1:1	Sheltered		
	11 ***	Roof, pitch 10-30 deg	1:1	Sheltered		
	12	Roof, pitch > 30 deg	··· 1:1	Sheltered	1.1	
	- 13	Long Wall	2:1	Exposed	WELL T	1
	. ft 14	Short Wall	1:2	Exposed		
	.15	Roof, pitch < 10 deg	2:1	Exposed	6 23	- 107 - Ū
	16	Roof, pitch 10-30 deg	2:1	Exposed		
	1.5 1 at 17 5	Roof, pitch $> 30 \deg$	2:1	Exposed		
	18	Long Wall	2:1	Semi-Exposed		8
	19	Short Wall 3 3 5 8	t k 👘 1:2 👘	Semi-Exposed	en filmen i	1.10
	20	Roof, pitch $< 10 \deg$	2:1	Semi-Exposed	1 - E.	
	21	Roof, pitch 10-30 deg	2:1	Semi-Exposed		ä
	22	Roof, pitch > 30 deg	2:1	Semi-Exposed		
17	. s r23, : son	Long Wall	2:1	Sheltered		3
	24	Short Wall	1:2	Sheltered		
- £ -	······································	Roof, pitch < 10 deg	· 2:1	Sheltered and	15 -	
1 .v-	* 26	Roof, pitch 10-30 deg	2:1	Sheltered		
	27	Roof, pitch > 30 deg	2:1	Sheltered		2
	28	Wall	1:1	Exposed	· · · · · ·	
	29	Roof, no pitch	1:1	Exposed		

TABLE 2 : Pressure Coefficient Data Sets Currently Available.

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CASE STUDIES

1. Ladywell High Rise

Recent years has seen increasing investment in upgrading of high rise tower blocks built in the 1950's and 1960's.

A small architectural practice was concerned with thermal upgrading of Ladywell high rise, a tower block in Glasgow comprising a number of similar 1 and 2 bedroom flats. Money was limited therefore a detailed computer simulation study was commissioned from EDAS to predict the most cost-effective options for upgrading in terms of occupant comfort, condensation risk, heating capacity required and energy consumption & cost.

As part of the study it was necessary to predict 'design' air infiltration rates for all rooms in each of the 1 and 2 bedroom flat types for two cases : (i) leaving existing ill fitting single glazing units unmodified or, (ii) replacing with new double glazed units incorporating trickle ventilators. Given the site microclimate details, it was decided that infiltration rates be predicted for both an easterly and westerly wind direction.

Figure 2(a) shows a general perspective view of a 1 bedroom flat, as developed for energy simulation modelling using the ESP package. Figure 2(b) shows a plan view of the flat with the distributed air leakage network superimposed.

Figure 3 shows similar information for the 2 bedroom model.

Design day simulations using representative hourly weather data for Glasgow gave predicted average air infiltration rates for each flat type as listed in Table 3, below.

TABLE 3 - Ladywell High Rise : Predicted 'Design Day' Average Air Infiltration Rates (air changes per hour).

1 22

1. 1-Bedroom Flat

		w 13	liv	kit.	hall	. bath	bed1	bed2
a)	Single Glaz	zing	2007 2017	and the second states	5 21 2 1 2	Ĥ		
	West wind	1	2.3	0.0	0.0	0.0	1.6	-
	East wind		0.0	3.1	1.8	3.9	0.0	-
b)	Double Glaz	zing	а: 		1			
	West wind	2	0.6 //	0.0	0.0	0.0	0.4	-
	East wind		0.0	0.4	1.2	0.5	0.0	-
		VAL SINE	NAT. PROTECTE PL	alle in States - 1.24	Read a service of the	•		
2.	2-Bedroom H	Flat/.						
		1.000	÷ 7.					

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Figure 3(b) : AIr Leakage Network

2. 2-Bedroom Flat

		1	iv	kit	1	hall	ł	báth	bedl	bed2	
a)	- Single Glazing	Į.	.1			ай <u>н</u>					
	West wind	2	.0	2.5		0.0		0.0	0.1	0.2	
	East wind	0	.1	0.0	a 3 K	2.0		5.1	0.3	0.5	
b)	Double Glazing		100 3			E.					
•	West wind .	0	.5	0.5		0.0	· .	0.0	0.1	0.2	
	East wind	0	.0	0.0		1.6		1.1	0.0	0.1	
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The simulations demonstrated the predicted effect of window replacement on air infiltration rates.

With regard to the global study which involved detailed thermal modelling as well as air infiltration prediction, it was concluded that window replacement outperformed proposed wall insulation upgrading as a means of reducing energy consumption & cost, but the reduction in predicted air infiltration meant increased condensation risk due to humidity build up.

2. Atrium Appraisal

A multi-storey building conversion project in Glasgow involved the architects in turning a central open lightwell into a glass covered atrium.

Amongst other things, the architects were concerned to establish whether there was any possibility of the atrium overheating in summer and, if so, whether a passive venting scheme based on temperature stratification could be employed to provide cooling using outside air.

A leakage network for the atrium was established, incorporating air inlets at ground level and openable louvres in the glass cover at high level. Figure 4 shows a simple perspective view of the atrium. Figure 5 shows the air leakage network.

The atrium leakage network was simulated in tandem with thermal simulation of the atrium using ESP. The results indicated that with the passive venting scheme as proposed, predicted summertime conditions within the atrium would be acceptable.

It should be stressed, however, that the author has strong doubts regarding the practical applicability of a crude nodal network air flow modelling technique for predicting air flow in an atrium. In most instances of interest the actual fluid flow patterns within the atrium are likely to be quite complex, requiring a more refined simulation approach such as might be adopted using a computational fluid dynamics (CFD) model.

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Figure 5 : Atrium Air Leakage Network.

3. The Crystal Pavilion

This project is, in many respects, similar to the atrium project above.

The Crystal Pavilion at the 1988 Glasgow Garden Festival was a fantasy exhibition building designed to house displays relating to crystals and crystalline technology. The appearance of the building was intended to reflect the crystalline concept and was loosely based on a quartz crystal cluster. Figure 6 shows a perspective view of the crystal pavilion from an ESP model. The building comprised solely of single skin glass, painted internally in shades of blue to enhance the crystalline effect.

The architects on the project were concerned to establish whether the pavilion would overheat in summer and, if so, whether mechanical cooling was needed or some form of passive ventilation scheme would suffice.

Based on the ESP model, it was predicted that, for a warm, sunny summer design day for Glasgow, use of outside air could influence peak internal temperatures as follows :

Infiltration a (per hour)	air cl	nange		Pred	dicted 1 (0	Peak Tempe leg.C)	erature
10		÷.,	5.3	$=$ \sim .	(m H. C.)	33.4	
30 50				1.0011		28.2	

The task then was to establish whether, under design conditions, around 30 plus air changes per hour could be induced on account of stack effect. An air leakage model was generated. Figure 7 shows the model which represents a crude simplification of the problem. Essentially, the pavilion was subdivided into a number of equivalent rectangular volumes sitting on top of each other. Simulations predicted that passive ventilation cooling was possible.

At the end of the day the architects decided that the inclusion of a significant area of air louvre on the external glass skin, needed for venting, would seriously degrade the visual appearance of the building. Thus, on the basis of simulation results, mechanical cooling plant was sized.

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Figure 6 : The Crystal Pawilion (Height = 15m) * 20m 2.5 where the set of the paper of the set of

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Figure 7 : Crystal Pavilion Air Leakage Network

4. John Brown Engineering

An engineering consultant was commissioned by John Brown Engineering to evaluate a number of options for replacement of heating systems in the main factory (known as the 'engine works') which comprises a number of individual 'bays' all linked together. Figure 8 shows perspective and plan views of a computer model of the engine works.

Part of the design involved prediction of values for design infiltration rate for each bay for use in sizing heating plant. The consultant commissioned EDAS to generate an air leakage model for the factory and use it to predict air infiltration rates for various conditions.

From site inspection and measurement, a detailed picture of the air leakage paths within the engine works was established. Figure 9 shows the resulting air leakage network which has, as leakage paths, doors, windows, fans, rooflights, eaves and ridge gaps.

The network was simulated against suitable 'design day' climate for the following scenarios :

- 1. Background leakage only. All (large) roller doors closed. All fans OFF, except for those in bay ew4 which are continuously removing air from an acid bath process.
- 2. All roller doors half open. All fans OFF, except in bay ew4.
- All roller doors closed. All fans in bays ew1, ew4 and ew18/19 ON.
- 4. Assumed that a gas turbine test was taking place in bay ew12. Consequently, all roller doors would be closed, except for bay ew12 roller door which would be one third open. Door between ew11 and ew12 closed. Fans in ew12 ON. All other fans OFF, except in bay ew4.
- 5. As simulation study 1, except background leakage areas increased slightly to account for additional ventilation area required for a certain type of direct fired radiant gas heater.

The simulation results were as follows :

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Figure 8(b) : Plan View of Engine Works

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 $\mathcal{L}_{i} = \{ p_{i} p_{i}^{*} | i \in I_{i} p_{i} \} \quad \forall i \in \mathcal{L}_{i} \} \quad \forall i \in \mathcal{L}_{i} \}$

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NOTE : N=north, S=south, W=west, E=east, R=roof. err = eaves, ridge & rooflight leakage.

Figure 9 : John Brown Engineering - Air Leakage Network

1		SIMULAT	ION NUMBER	R	
BAY	1	2	3	4	5
-					
ewl	0.90	3.75	0.61	0.90	0.90
ew2	0.36	3.88	0,62	0.36	0.36
ew3	0.02	0.01	0.23	0.02	0.02
ew4	1.63	0.94	1.88	1.63	1.63
ew5	0.10	8.08	0.17	0.10	0.10
ew6		no infi	ltration p	oredicted	
ew7	0.08	6.38	0.08	0.08	0.08
ew8		no infi	Itration)	oredicted	
ew9	0.33	0.19	0.33	0.33	0.33
ew10	0.82	6.57	0.82	0.82	0.82
ew11	0.77	8.91	0.77	0.77	0.77
ew12	1.93	5.69	1.93	6.16	1.93
ew18/19	0.20	4.68	0.20	0.20	0.20
AVERAGE	0.55	3,78	0.59	0.87	0,55
		5,75			0.0

TABLE 4 : John Brown Engineering : Average Predicted Infiltration rates for design day.

These results were used as the basis for selecting 'design' infiltration rates for heating system sizing.

FOOTNOTE FOR BEPAC AIR MOVEMENT TASK GROUP MEMBERS

To go into the above case studies in great detail would result in a very lengthy paper. Consequently it is proposed that a limited number of copies of the **mfs** fluid flow model be made available to task group members. The software currently runs on UNIX workstations, but is being ported onto an IBM compatible PC. A manual is currently being written, which will include the four case studies outlined in this paper as demonstration material. The user will be able to re-run the simulations carried out in the above case studies, make modifications and generate his/her own air leakage networks for any other application.

Full details of this proposal will be sent to members with the minutes of this meeting.