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A Survey of Air Flow Models for Multizone Structures

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Abstract

Air flow 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 by using multizone air flow models. In order to obtain more information on multizone air flow models, a literature review was performed in 1984 [1]. A second literature review and a questionnaire survey performed in 1989, revealed the existence of 50 multizone air flow models, all developed since 1966, two of which are still under development. All these programs use similar flow equations for crack flow, but differ in the versatility to describe the full range of flow phenomena and the algorithm provided for solving the set of nonlinear equations. This literature review has found that newer models are able to describe and simulate the ventilation systems and interrelation of mechanical and natural ventilation.

Introduction

Air flow 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. Air flow models can be divided into two main categories, single zone models and multi-zone models. Single zone models assume that the structure can be described by a single, well mixed zone. The major application for this model type is the single-story, single-family house with no internal partitions (e.g., all internal doors are open). A large number of buildings, however, have structures that would characterize them more accurately as multizone structures, more detailed models have been developed, which also take internal partitions into account. Figure 1 shows a simple multizone network [2].

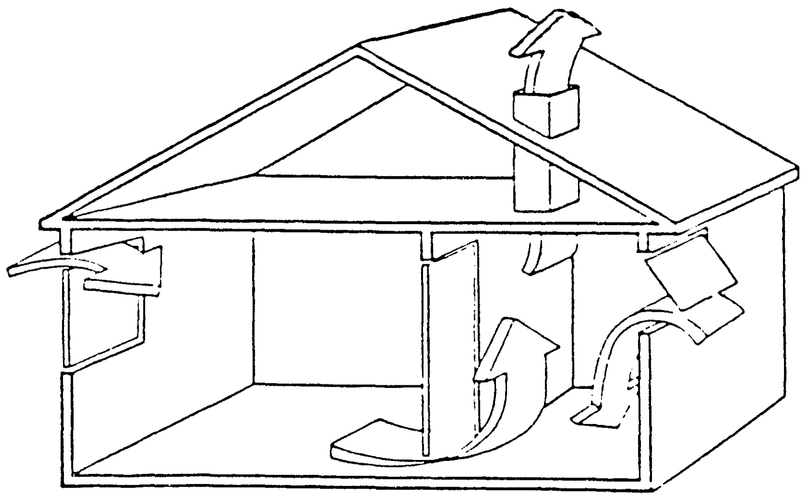

Figure 1: Simple Multizone Network

Multizone air flow network models deal with the complexity of flows in a building by recognizing the 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 in predicting flow for simple structures such as single-family residences [3].

As for their single-zone counterparts, these models are based on the mass-balance equation. Unlike the single-zone approach, where there is only one internal pressure to be determined, the multizone models must determine one pressure for each of the zones. This adds considerably to the complexity of the numerical solving algorithm, but by the same token, the multizone approach offers great potential in analyzing infiltration and ventilation air flow distribution.

The advantage of multizone models, besides being able to simulate infiltration in larger buildings, is their ability to calculate mass flow interactions between the different zones. Understanding the air-mass flow in buildings is important for several reasons :

- exchange of outside air with inside air is necessary for building ventilation
- energy consumed to heat or cool the incoming air to inside comfort temperature
- air needed for combustion
- airborne particles and germs transported by air flow in buildings
- 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 also influence the air flow. The openings can be varied by the inhabitants. This can lead to significant differences in the pressure distribution inside the building. Figure 2 shows in detail the influence of pressure distribution on the air-mass flow distribution.

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 including the flow resistances caused by open or closed doors and windows or background leakage of the partitions. 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 of 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 density difference between outside and inside air. Differences in density of the air, due to differences between outside and inside air temperatures or moisture content, 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 path ways, 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 non-linear 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. Large quantities of computer storage was necessary for the early models to describe buildings with arbitrary floor plans and to solve the set of non-linear equations.

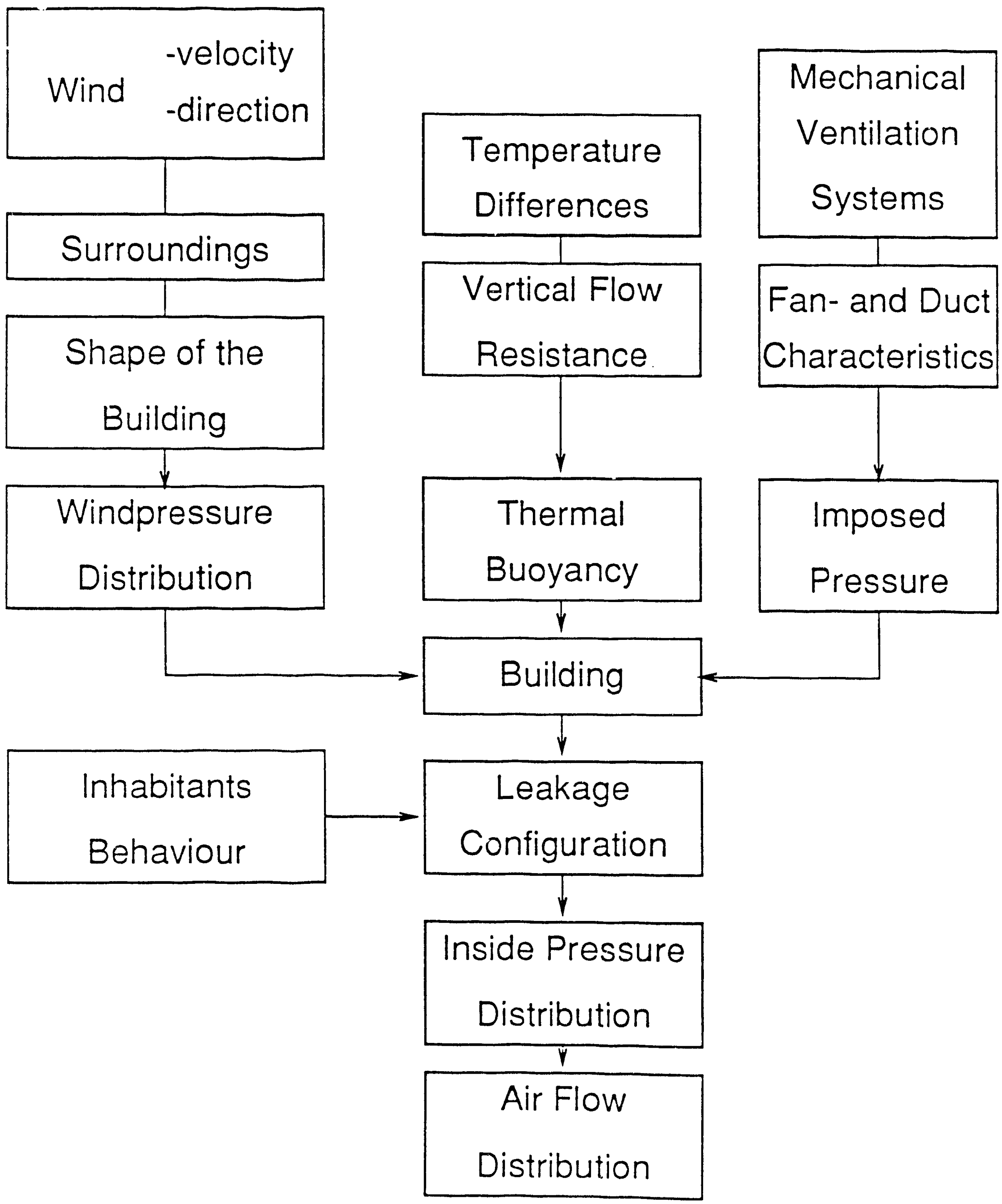

Figure 2 : Influence of Pressure Distribution on the Air-Mass Flow in Buildings

Literature Review and Questionnaire Survey

A literature review undertaken in 1984 [1] revealed 26 papers describing 15 different multizone infiltration models which had been developed in eight countries. A recent questionnaire survey produced additional information about the status of network models. One of the first models we found was Jackman's model "LEAK" [4] which was published in 1970. In 1974 it was followed by the NRCC model [5], which was the first one available to interested parties. Indeed, this numerical tool is probably still the most widely used multizone infiltration model.

Several multizone models were developed in the aftermath of the oil price crises. Between 1975 and 1977 a series of steps were taken at Technische Universitaet Berlin to develop such a model. This resulted in the program STROM [6] which was later extended to handle HVAC-systems and has recently been rewritten to improve the solver and to be combined with a thermal building simulation model [7]. Concurrent with STROM, ELA 4 [8] was developed. The models VENT 1 and VENT 2 [9] as well as BREEZE [10] were developed in the late 1970's by researchers from British Gas and the Building Research Establishment. In the early 1980's, the first versions of Nantka's INFILTRATION & VENTILATION [11], Walton's AIRNET [12] and Herrlin's MOVECOMP [13] appeared. The latter two programs were the first to address the mathematical problem of solving the set of non-linear equations for zones with very different leakage characteristics. Open doorways in otherwise tight constructions are the main cause of significant problems in convergence. This has been solved by introducing under-relaxation factors to the well known Newton method.

KGVCP from Hayakawa dates back to 1979 [14]. More recent work done in Japan has been published by Ishida and Udagowo [15] as well as Hayashi and Urano [16], Sasaki [17], Okuyama [18] and Matsumoto and Yoshino. [19].

France has also developed several multizone models; the recent survey unveiled models from CSTB, INSA [20] and EDF. From Brazil, Melo's model FLOW2 [21] has been discovered.

The latest development in infiltration modeling is the COMIS model [22]. In a twelve month period ten scientists from nine countries, working together at Lawrence Berkeley Laboratory, developed a multizone model on a modular base. Because of its modular structure COMIS is designed to expand its capability to simulate buildings. To accomplish a "user-friendly" program, special emphasis was given to input and output routines. Support of the international group by IEA's Air Infiltration and Ventilation Centre will help the wide distribution of this model to all interested parties. COMIS can be used as a stand-alone infiltration model with input and output features, or as an infiltration module for thermal building simulation programs. It also serves as a module library.

One of the major tasks for the program user is to find a method of determining the wind pressure distribution for a building. This can be done by measuring the wind pressure distribution on a scale model in a wind tunnel or by using measured data from available literature. Only few attempts have been made to calculate the wind pressure distribution. In order to calculate the Cp-distribution for buildings, the COMIS group worked on a method based on a parametrical study, to determine the Cp-values [23].

Crack flow, large openings and mechanical ventilation systems can be simulated by some of the models. Furthermore, additional flows, i.e., simultaneous two way flow at large openings and wind turbulence effect at single-sided windows etc., were studied.

Airflow rates through doorways, windows and other common large openings are significant ways in which air, pollutants and thermal energy are transferred from one zone of a building to another.

In the previous survey of multizone infiltration models, however, none of the described codes were able to solve this problem in any other way than to divide the large opening into a series of small ones described by crack flow equations.

Therefore, COMIS's contribution to this fundamental problem was to describe the physical problem, review the various solutions developed in the literature and compare these solutions using both a numerical and a physical point of view.

In most cases the temperature of the air in a crack is quite different from the temperatures of the zones on either side of the crack. Furthermore, air leakage performance measurements are usually performed in a certain temperature condition, but results are used at different temperatures. The temperature variation, however, has a big influence on the air leakage flow due to changes in the air viscosity and air density. Unfortunately, almost all the models dealing with air leakage characteristics ignore this phenomenon.

HVAC-Systems (Heating, Ventilating and Air-Conditioning Systems) are composed of ducts, duct fittings, junctions, fans, air filters, heating and cooling coils, air-to-air heat exchangers, flow controllers, etc. Several modeling programs for ventilating systems were developed.

Calculating the infiltration and ventilation flow rates requires the solution of a non-linear system of equations. The main task is to find an efficient solving method. The starting point is the Newton-Raphson method, with derivatives, operating on a node-oriented network which, in most cases, quickly brings about the convergence of the system of equations.

Although network computer models are available, there is an obvious need for simplified multichamber infiltration models capable of providing the same accuracy as the established single-cell models. The extended crack model is the simplest multizone model. It is used to design conditioning loads and size the conditioning equipment [24]. The method is based on the single-zone crack model and has been refined to multizone applications by also taking into consideration the crack flow through internal partitions. Buildings are characterized according to their cross flow and stack flow capabilities. The stack pressures of the core zones for multistory structures are pre-calculated for design weather conditions and published in look-up tables. Together with pressures due to the effect of wind and permeability distribution this enables a user to calculate the infiltration for each of the outside zones.

The simplified multizone infiltration model developed at LBL [25] is able to calculate the air flow distribution for arbitrary structures in any given weather condition. The basic idea is to determine the flow network and to calculate the resultant air permeability of a zone from the combination of flow paths arranged in series and/or parallel. The use of these equations assumes that all permeabilities have the same flow characteristics and, therefore, the same exponent, n.

Air flows caused by separate mechanisms (such as wind and thermal buoyancy) are not able to be added because the flow rates are not linearly proportional to the pressure differences. To superimpose the flows, it is necessary to add the pressures.

Several lumped parameters reflecting the different permeability distributions of the building's envelope and the flow resistances inside the building were introduced to describe the air flow distribution. To keep the model simple no mass-balance equation is used to predict the air flows. Because of the pre-calculation of the simplified network, the model gives a comprehensive understanding of the flow characteristics of the structure under investigation. The model is simple to use and requires only simple mathematical tools, e.g., pocket calculator.

In terms of the total number of returned questionnaires this survey represents the most comprehensive review of current research in developed multizone infiltration models. The questionnaires were mailed to addresses provided by the Air Infiltration and Ventilation Centre [26,27]. Fifty multizone infiltration models developed in 16 countries are represented in this survey. In addition to the general references more than 60 paper describing the programs in detail are listed in Appendix B together with the names and addresses of the authors. Of those models for which questionnaires were not returned, information was collected from the reviewed literature.

In cases where the reviewed paper did not give a reasonable answer to a certain problem or where information was missing from a returned questionnaire, a question mark was entered in the list of models.

The summarized list of multizone air flow models found in the literature are reproduced in Appendix A. The current addresses of the authors including their references are shown in Appendix B. Equations are reproduced separately in Appendix C.

Discussion

The survey of multizone network models is summarized in Table 1. It shows that 34 models have been written in FORTRAN (FORTRAN IV (F IV), FORTRAN V (F V), and FORTRAN 77 (F 77). The programming language BASIC has been used four times; followed by HPL with three and "C" with two applications. PASCAL and dBaseIV have been used for the development of one model each.

Among the analyzed models it appeared that 14 were developed on main frame computers, 15 on PC's and 11 on workstations.

In the past large amounts of computer storage was necessary, when calculating the air flow distribution of more complicated buildings. Nowadays most programs use solvers which reduce the space requirement, e.g., band matrices or the skyline method. The Newton method is the most common tool used to solve the set of nonlinear equations. The majority of the programs use a technique based on Newton-Raphson. Other Algorithms are used less frequently.

The limits of zones and openings per zone a model can handle depends on computer storage. Due to the limited availability of computer storage most of the earlier models were not able to handle more than 100 zones. Models developed later are able to handle an unlimited number of zones.

Approximately 1/3 of the models do not have an interactive input option and the output features listed show that only few models use graphical output or statistical functions rather than files comparable to the arrays used by the model. These features are an indication of a user unfriendly model. CAD - Input and 3 - D building description are not necessary to run the program, but would increase the user-friendliness. Unfortunately, these input features belong to the "special design", and are rarely integrated in these kind of models.

Only 19 models take into consideration occupant schedules which can lead to significant differences in the pressure distribution.

The output features show that the graphical output and the statistical functions are less applied than files used by the model.

Twentyfour of the models use a separate input program and twenty models are based on a modular structure. A modular structure might be more advantageous for further development, because the model would be easier to expand. A combination with other models would also be easier to implement.

Fifteen of the models allow a combination with a thermal model and thirteen models are coupled with a pollution model.

Less than one third (15) of the models are available to third parties. Some models are not available before completing and testing. Fifteen models are not available to the public and are written as research tools, rather than for the use of professional engineers or architects.

Table 1 : Review of Multizone Air Flow Infiltration Network Models

Program Language :			
FORTRAN	34		
BASIC	4		
PASCAL	1		
C	2		
HPL	3		
dBaseIV	1		
Computer Type :			
Main Frame Computer	14		
Work Station	11		
Personal Computer	15		
Solver :			
Hardy - Cross - Method	1		
Newton - Raphson Method	25		
Levenberg - Marquard - Method	1		
Brown - Conte - Method	1		
Secant - Method	3		
Rule "falsi"	1		
Gaussian - Elimination	1		
Beta - Method by Newmark	1		
Limits :	**$\leq$ 100**	**> 100**	**unlimited**
max. number of zones	18	7	18
max. number of opening/zone	17	3	23
max. number of shafts/corridors/floors	17	2	23
max. number of mechanical ventilation system	18	2	20
Input Features :	**yes**	**no**	**not specified**
interactive input	15	21	14
CAD input	1	30	19
weather data from weather files	24	14	13
3 - D building description	10	26	14
schedules (e.g., occupants)	19	17	14
Output Features :	**yes**	**no**	**not specified**
file of arrays used by the model	29	6	15
graphical output	12	23	15
statistical functions	5	29	16
Structure :	**yes**	**no**	**not specified**
separate input program	24	14	12
modular structure	20	14	16
Combination with other models :	**yes**	**no**	**not specified**
combined with thermal model	15	24	11
combined with pollution model	13	26	11
Availability :	**no**	**yes**	**yes, but**
program available to third parties	15	15	12

Conclusion

This literature review and the questionnaire survey show that an extensive research effort has been made in the last five years to develop an air flow model for multizone structures. Especially the maximum number of zones the models can handle has been increased due to reduced computer storage requirements. Some of the models have been extended with special input and output features.

Fifteen of the models are available to third parties and fifteen models have been written as research tools, and are difficult to use. This might be the reason they are not available to third parties.

The development of multizone infiltration and ventilation models shows a relatively slow evolution. Lack of exchange of information, restricted distribution of models, poor documentation, and lack of a flexible structure are probably the reasons why models developed in the early seventies are not very different from those developed in the late eighties.

Although several of the models discovered during this survey serve a particular purpose, they could have been developed using existing models. The COMIS workshop was trying to overcome these problems by creating a multizone infiltration model with a modular structure which will allow modules to be changed easily. The availability of the program and its documentation together with the international authorship should help to establish COMIS as an infiltration standard on which specific applications can be built.

Future Outlook

Along with stand-alone infiltration models, network models will also find their way into thermal building simulation models. With the expected advances in the development of the next generation of building simulation programs, infiltration modules will be needed for implementation in the program libraries.

Future tasks include the development of methods to determine the required input parameters, especially the wind pressure distribution. Further work must be done through sensitivity studies to reduce the input requirement and to increase user-friendliness by using the output features of the PC's.

Validation of the models is another essential task. In order to understand physical phenomena related to transport mechanism in buildings and to develop numerical descriptions, measurements must first be performed under steady state conditions. It is necessary, in order to measure mass flow transport mechanism accurately, to be able to control the pressure level and its fluctuation for each of the outside walls. This is only possible if the test building itself is located in a building. Such a test facility would not only validate air flow models as a whole, but would also help to validate the tracer gas techniques used to validate infiltration models in field experiments.

Recent developments in measurement techniques open new possibilities to study physical phenomena and use the results for comparison with results from the model. Some data sets for evaluation purposes have been produced based on in-situ measurements of heavy instrumented buildings. Before these data sets can be used for model evaluation, however, internal model comparisons based on benchmark buildings have to be performed.

The Energy Conservation in Buildings and Community Systems Program of the International Energy Agency adopted a new working group (Annex 23) to study physical phenomena causing air flow and pollutant transport (e.g., moisture) in multizone buildings and to develop modules to be integrated in a multizone air flow modeling system. The system itself shall be user-friendly and structured to be incorporable in thermal building simulation models. Furthermore, special emphasis shall be given to provide data necessary to use the system (e.g., wind pressure distribution, default values for leakage of building components, material properties like absorbtion and desorption). The comparison between results from the model and from in-situ tests is an important part of this annex.

Close cooperation is envisaged, with regard to state-of-the art reviews, data collection, coordination of work, e.g., defining cases for evaluation purposes with other pertinent projects. The work to be carried out will be complementary with the above mentioned Annexes.

The Air Infiltration and Ventilation Centre will, as part of its on-going work plan, act as a vehicle for disseminating the results of this particular Annex. A data base for evaluation purposes is going to be prepared by AIVC. The Centre has already started to collect wind pressure data and leakage data.

Acknowledgements

We would like to acknowledge the program authors for their cooperation in responding to our questionnaires, for without this information the different programs could not have been summarized.

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APPENDICES

The following appendices describe the reviewed literature and the results of the questionnaire survey in a tabular form. Fifty different multizone air flow models are listed in Appendix A. A question mark was entered in the table of models where the reviewed paper did not give a reasonable answer to a certain problem or where information was missing from the returned questionnaire. The authors of the models can be found in Appendix B. Together with the authors of the computer models and their current addresses, more than 60 papers describing the models in detail are listed in Appendix B. Equations used by the models as well as a nomenclature are shown separately in Appendix C.

APPENDIX A - List of Multizone Air Flow Models

Number (for authors see Appendix B)	1	2	3	4	5	6	7	8	9	10	11
General											
-name	see[1.1]	see[2.1]	?	PSSP/MV1[4.1]	ETIMCELL	VENT	see[7.1]	see[8.1]	NETS	S3PAS	GAINE
-program-language[0.1]	F + Basic	?	F77 + MS	F 77	Pascal	F 77	Basic	F	F	F 77	F IV
-written for computer type[0.2]	PC	?	M / PC	M / PC[4.2]	PC	M	PC	M	M	WS	WS
-written for operating system	MS-DOS/DOS	?	?	?[4.2]	MS-DOS 3.3	--	?	?	--	VMS	VMS
Equations[0.3]											
-flow through cracks	1 G	1 D	1 E	1 E	1 E	1 B	1 E	1 E	1 K	1 E	1 A
-flow through large openings	2 D	1 D	2 D	2 D	2 D	2 D	2 D	2 G	2 I	2 D	--
-flow through duct work	3 B	1 D	--	--	3 C	?	3 E	3 E	3 G	--	3 E
-fan flow characteristics	4 E	--	4 A	constant	4 B	?	4 E	--	4 G	4 C	4 C
-wind pressure	5 C	--[2.2]	5 D	5 C	5 B	5 E	5 D	5 C	5 C	5 B	5 C
-thermal buoyancy	6D	6D	6B	6D	6 B	--	6 B	6 D	6 J	6 B	6 B
-outside pressure fluctuation	constant	--	--	--	--	--	7 A	--	--	--	constant
-circulation flow on large openings	yes	?	?	yes	yes[5.2]	--	--	--	--	--	--
-single sided ventilation	yes	?	?	yes[4.3]	--	--	?	?	--	--	?
-cross ventilation	yes	?	?	8 D	--	--	?	?	--	--	?
-pressure coefficient (only if calculated)	--	?	?	yes	yes[5.3]	--	?	?	--	11 A	constant
-temperature gradient	yes	?	12 A	--	constant	--	?	?	constant	--	?
Algorithm To Solve Nonlinear Set Of Equation[0.4]											
-name of algorithm[0.5]	N - R	Iteration	N - R	Newton[4.4]	see[5.4]	?	N - R	rule "falsi"	MNR	see[10.1]	Newton
-equation	13 C	13 D	13 C	13 F	?	13 A	13 B	13 D	see[9.1]	13 A	13 E
Limits											
-max. number of zones	100	2 or 3	20	unlimited	see[5.5]	8	?	?	300	10	unlimited
-max. number of openings/zone	20	2 or 3	20	unlimited	?	12	?	?	900	33	unlimited
-max. number of shafts/corridors/floors	20	--	?	unlimited	?	2	?	?	300	unlimited	unlimited
-max. number of mechanical ventilation systems	unlimited	--	20	unlimited	?	--	?	?	900	100	unlimited
Input											
-interactive input	?	no	no	no	yes	no	yes	no	no	yes	no
-CAD-input	no	no	no	no	no	no	yes	no	no	no	?
-weather data from weather files	no	no	yes	yes	yes/no[5.6]	yes	yes	yes	yes	no	yes
-3-D building description	no	no	no	no	yes	no	yes	no	yes	no	no
-schedules (e.g., occupants)	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
Output											
-file of arrays used by the model	?	no	yes	yes	yes	no	yes	no	yes	yes	yes
-graphical output	no	no	no	no	no	no	no	no	yes	yes	yes
-statistical functions	no	no	no	no	no	no	no	no	no	no	yes
Structure											
-separate input program	?	no	yes	yes	yes	yes	no	no	yes	yes	yes
-modular structure	?	no	no	no	yes	no	yes	yes	yes	yes	yes
Combination With Other Models											
-combined with thermal model	yes	no	yes	yes	no	no	no	no	yes	yes	no
-combined with pollution model	yes	no	no	no	no	no	no	no	yes	no	yes
Program Availability											
-program available to third parties	no	yes, but[2.3]	no	yes[4.5]	yes, but[5.7]	yes	no	no	yes, but[9.2]	?	no

Number (for authors see Appendix B)	12	13	14	15	16	17	18	19	20	21	22
General											
-name	SIREN2	JKCIRCUS	see[14.1]	--	see[16.1]	see[17.1]	SSPV-7	AIRNET	MOVECOMP-PC	--	VENCON
-program-language[0.1]	F IV	F	F 77	F	F	F	F 77	C	F 77	F	HP Basic 4.0
-written for computer type[0.2]	WS	WS/PC	?	?	PC	WS	?	PC	M/PC	M/PC	series 200
-written for operating system	VMS	VMS/MS-DOS	?	?	MS-DOS	VAX	?	MS-DOS	MS-DOS	NCOS/DOS	HP Basic 4.0
Equations[0.3]											
-flow through cracks	1 A	1 G	1 E	1 A	1 A	1 B	1 G	1 A + 1 J[19.1]	1 A	1 A	1 G + 2 F
-flow through large openings	2 A	2 K	2 D	2 A	2 D	?	2 D	2 A + 2 H[19.1]	2 A	2 A	1 G + 2 F
-flow through duct work	3 B	3 H	--	?	3 B	?	--	3 F	3 H	--	3 E
-fan flow characteristics	4 C	--	4 B	?	4 A	?	4 B	4 F	yes[20.1]	--	4 A
-wind pressure	5 C	5 B	5 C	5 B	5 A	?	5 B	5 C	5 D	5 B	5 B
-thermal buoyancy	6 B	constant	6 B	?	6 H	?	6 B	6 A	6 D	6 B	6 G
-outside pressure fluctuation	constant	--	?	?	?	?	--	--	--	--	7 B
-circulation flow on large openings	--	--	?	?	?	?	--	yes	--	1 A	yes
-single sided ventilation	?	--	?	?	?	?	--	--	--	--	yes
-cross ventilation	?	..	?	?	?	?	--	yes	--	1 A	yes
-pressure coefficient (only if calculated)	constant	--	?	?	?	?	11 B	--	constant	--	--
-temperature gradient	?	--	?	?	12 B	?	--	--	12 C	no	yes
Algorithm To Solve Nonlinear Set Of Equations[0.4]											
-name of algorithm[0.5]	Lev - Mar	Gauss	Bro - Con	N - R	?	Beta	N - R	N - Steff	N-R[20.2]	N - R	Sec - Met
-equation	13 F	13 G	see[14.2]	?	?	?	13 B	13 E or 13 H	13 H	13 E	see[22.1]
Limits											
-max. number of zones	40	unlimited	unlimited	?	30	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
-max. number of openings/zone	unlimited	unlimited	unlimited	?	20	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
-max. number of shafts/corridors/floors	1	unlimited	unlimited	?	20	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
-max. number of mechanical ventilation systems	unlimited	unlimited	unlimited	?	10	unlimited	unlimited	unlimited	unlimited	--	400
Input											
-interactive input	no	no	yes	yes	no	?	no	yes	no	yes	no
-CAD-input	?	no	?	no	no	?	no	no	no	no	no
-weather data from weather files	yes	no	yes	no	yes	yes	yes	no	yes	no	no
-3-D building description	no	no	?	no	yes	?	yes	no	no	yes	no
-schedules (e.g., occupants)	yes	no	yes	no	no	no	?	yes	no	no	no
Output											
-file of arrays used by the model	yes	yes	yes	yes	?	yes	yes	no	yes	no	yes
-graphical output	no	no	yes	no	?	?	no	no	no	no	yes
-statistical functions	no	no	?	no	?	?	no	no	yes	no	yes
Structure											
-separate input program	yes	no	yes	yes	no	yes	no	yes	yes	no	no
-modular structure	yes	no	?	no	no	?	no	yes	yes	no	yes
Combination With Other Models											
-combined with thermal model	no	no	yes	no	no[16.2]	no	yes	no	no	no	yes
-combined with pollution model	yes	no	no	no	no	no	yes	no	no	no	no
Program Availability											
-program available to third parties	no	yes	no	?	no[16.3]	limited	no	yes	yes	no	no

Number (for authors see Appendix B)	23	24	25	26	27	28	29	30	31	32	33[33.1]
General											
-name	INFILTR	ICARE	TONY	STROM-II	?	FLOW2	CP 37[29.1]	PAFDPIM	CLIM	?	COMERL
-program-language[0.1]	F 77	Basic	F 77	F V	F	F 77	F	Basic	F 77	F 77	dBaseIV
-written for computer type[0.2]	PC	HP-series 200	M/PC	M	M	VAX/IBM	M/PC	PC	?	M/WS	PC
-written for operating system	MS-DOS	HP Basic 3.0	VMS-DOS	?	?	VMS	?	DOS	?	Ultrix	DOS
Equations[0.3]											
-flow through cracks	1 L	1 G	1 G	1 E	1 C	1 B	1 F	1 B	1 M	1 H	1 A
-flow through large openings	2 J	--	2 D	2 D	2 C	2 D	2 E	2 D	2 K	2 D	2 L
-flow through duct work	3 I	3 C	--	3 B	--	--	--	3 J	?	3 D	3 J
-fan flow characteristics	--	4 E	4 E	4 B	--	--	--	4 H	?	4 D	4 E
-wind pressure	5 B	5 D	5 D	5 D	5 B	5 B	5 F	--	5 G	5 B	5 C
-thermal buoyancy	6 B	6 A	6 B	6 B	6 C	6 C	6 D	--	6 I	6 F	6 J
-outside pressure fluctuation	--	--	--	--	--	constant	--	--	--	--	constant
-circulation flow on large openings	--	--	--	--	--	8 A	--	--	8 B	--	8 C
-single sided ventilation	constant	--	--	?	?	--	--	--	--	?	yes[33.2]
-cross ventilation	constant	yes	yes	?	?	--	--	--	12 A	?	yes[33.2]
-pressure coefficient (only if calculated)	?	yes	--	--	?	yes[28.1]	--	--	--	?	yes[33.3]
-temperature gradient	?	--	--	--	?	12 D	--	--	--	?	constant
Algorithm To Solve Nonlinear Set Of Equation[0.4]											
-name of algorithm[0.5]	?	Newton	Newton	Newton	HCR	SOLVP	Newton	Newton	Sec-Met	Newton	see[33.4]
-equation	13 B	13 D	13 D	13 B	13 C	13 D	13 D	?	13 I	--[32.1]	--
Limits											
-max. number of zones	200	4	unlimited	150	unlimited	unlimited	25	4	25	60	unlimited
-max. number of opening/zone	3500	--	unlimited	unlimited	unlimited	unlimited	4	7	10	unlimited	unlimited
-max. number of shafts/corridors/floors	--	5	unlimited	unlimited	unlimited	unlimited	8	--	?	10	unlimited
-max. number of mechanical ventilation	--	5	unlimited	6	unlimited	unlimited	?	2	4	unlimited	unlimited
Input											
-interactive input	no	yes	no	yes	?	no	no	yes	?	?	yes
-CAD-input	no	no	no	no	?	no	no	no	?	?	no
-weather data from weather files	no	yes	yes	no	?	yes	no	no	yes	?	yes
-3-D building description	yes	no	no	yes	?	no	no	no	no	?	no
-schedules (e.g., occupants)	no	yes	yes	?	?	no	no	no	?	?	yes
Output											
-file of arrays used by the model	yes	yes	yes	yes	?	yes	yes	no	?	?	yes
-graphical output	no	yes	no	no	?	yes	no	no	yes	?	yes
-statistical functions	no	yes	no	no	?	no	no	no	yes	?	no
Structure											
-separate input program	yes	yes	yes	yes	?	yes	no	no	no	?	yes
-modular structure	yes	yes	yes	yes	?	yes	yes	no	no	?	yes
Combination With Ohter Models											
-combined with thermal model	no	yes	yes	yes	?	yes	no	no	yes	?	no
-combined with pollution model	no	no	no	no	?	yes	no[29.2]	no	no	?	yes
Program Availability											
-program available to third parties	?	yes	yes	no	yes	yes,but[28.2]	yes	yes,but[30.1]	no	?	unclear yet

Number (for authors see Appendix B)	34	35	36	37	38	39	40	41	42	43	44
General											
-name	?	?	TARP	?	Vent	?	?	SAFM[41.1]	?	?	?
-program-language[0.1]	F 77	F IV	F 77	F IV	F 77	HPL	HP-Special	--	?	?	F
-written for computer type[0.2]	VAX	M	?	M	IBM compatible	PC	PC	--	?	?	ICL 1907
-written for operating system	?	?	?	?	MS DOS	?	?	--	?	?	?
Equations[0.3]											
-flow through cracks	1 G	1 F	1 A	1 B	1 M	1 E	1 E	1 B	1 E	1 E	1 E
-flow through large openings	--	2 E	2 A	2 B	2 B	2 F	--	--	--	?	?
-flow through duct work	3 A	constant	--	--	?	3 E	--	--	3 C	?	?
-fan flow characteristics	yes	--	--	4 A	see[38.1]	4 E	--	--	4 C	?	?
-wind pressure	5 E	yes	5 A	5 B	5 F	5 B	5 D	5 H	5 B	?	?
-thermal buoyancy	6 B	6 D	6 A	6 B	6B, 6C, 6J	6 G	6 B	6 K	6 E	?	?
-outside pressure fluctuation	yes	--	constant	--	?	7 B	--	--	--	?	?
-circulation flow on large openings	--	--	yes	--	?	--	--	--	--	?	?
-single sided ventilation	?	?	--	?	?	?	?	--	?	?	?
-cross ventilation	?	?	yes	?	?	?	?	--	?	?	?
-pressure coefficient	?	?	--	?	?	?	?	11 C	?	?	?
-temperature gradient	?	?	--	?	?	?	?	--	?	?	?
Algorithm To Solve Nonlinear Equation[0.4]											
-name of algorithm[0.5]	--	?	N - Steff	N - R	N - R	Sec - Met	--	--	?	?	?
-equation	13 A	13 D	13 E	13 B	13C,13E,13H,13I	13 D	see[40.1]	--	?	?	?
Limits											
-max. number of zones	725	25	see[36.1]	300	100	50	see[40.2]	unlimited	?	?	211
-max. number of openings/zones	unlimited	4	see[36.1]	120	100	see[39.1]	see[40.3]	unlimited	4	?	4
-max. number of shafts/corridors/floors	5,720,720	1	see[36.1]	unlimited	?	see[39.1]	unlimited	unlimited	1, 0, ?	?	1, ?, 10
-max. number of mechanical ventilation	20	8	see[36.1]	unlimited	100	see[39.1]	--	--	?	?	?
Input											
-interactive input	?	?	--	?	yes	?	?	no	?	?	?
-CAD-input	?	?	--	?	no	?	?	no	?	?	?
-weather data from weather files	?	?	yes	?	?	?	?	no	?	?	?
-3-D building description	?	?	yes	?	?	?	?	no	?	?	?
-schedules (e.g., occupants)	?	?	yes	?	?	?	?	no	?	?	?
Output											
-file of arrays used by the model	?	?	--	?	yes	?	?	no	?	?	?
-graphical output	?	?	--	?	?	?	?	no	?	?	?
-statistical functions	?	?	--	?	?	?	?	no	?	?	?
Structure											
-separate input program	?	?	yes	?	yes	?	?	no	?	?	?
-modular structure	?	?	no	?	yes	?	?	no	?	?	?
Combination With Other Models											
-combined with thermal model	?	?	yes	?	no	?	?	no	?	?	?
-combied with pollution model	?	?	yes	?	yes	?	?	no	?	?	?
Program Availability											
-program available to third parties	limited	yes	limited	limited	yes,but[38.2]	no	no	yes	?	?	yes

Number (for authors see Appendix B)	45	46	47	48	49	50
General						
-name	?	VENT 1	VENT 2	COMIS	CONTAM88	DTFAM
-program-language[0.1]	?	F 77	Basic	F 77	C	F77
-written for computer type[0.2]	?	M	PC	MicroVAX,PC	IBM comp	IBM com
-written for operating system	?	?	?	Unix, MS-DOS	MS-DOS	MS-DOS
Equations[0.3]						
-flow through cracks	1 D	1 D	1 D	1 A	see[49.1]	see[50.1]
-flow through large openings	2 G	2 D	2 D	2 L	see[49.1]	see[50.1]
-flow through duct work	2 G	--	--	3 J	see[49.1]	see[50.1]
-fan flow characteristics	?	constant	constant	4 E	see[49.1]	see[50.1]
-wind pressure	?	5 C	5 C	5 C	?	?
-thermal buoyancy	?	6 B	6 B	6 J	?	?
-outside pressure fluctuation	?	7 A	7 A	constant	--	--
-circulation flow on large openings	?	--	--	8 C	yes	yes
-single sided ventilation	?	--	--	yes[48.1]	--	--
-cross ventilation	?	--	--	yes[48.1]	?	?
-pressure coefficient (only if calculated)	?	--	--	yes[48.2]	?	?
-temperature gradient	?	--	--	constant	uniform	uniform
Algorithm To Solve Nonlinear Set Of Equation[0.4]						
-name of algorithm[0.5]	Newton	see[40.1]	see[47.1]	see[48.3]	N - R	N - R
-equation	?	?	?	13 B	?	?
Limits						
-max. number of zones	150	40	2	unlimited	unlimited	unlimited
-max. number of openings/zones	?	unlimited	40	unlimited	unlimited	unlimited
-max. number of shafts/corridors/floors	?	40, 40, 40	0	unlimited	unlimited	unlimited
-max. number of mechanical ventilation systems	?	1/opening	1	unlimited	unlimited	unlimited
Input						
-interactive input	?	yes	yes	yes	no	no
CAD-input	?	?	?	no	no	no
-weather data from weather files	?	yes	no	yes	yes	yes
-3-D building decription	?	no	no	no	yes	yes
-schedules (e.g., occupants)	?	no	no	yes	yes	yes
Output						
-file of arrays used by the program	?	no	no	yes	yes	yes
-graphical output	?	yes	yes	yes	no	no
-statistical functions	?	no	no	no	no	no
Structure						
-separate input program	?	yes	no	yes	yes	no
-modular structure	?	?	?	yes	yes	yes
Combination With Other Models						
-combined with thermal model	?	yes	no	no	no	yes
-combined with pollution model	?	yes	no	yes	yes	no
Program Availability						
-program available to third parties	?	limited	limited	yes[48.4]	yes[49.2]	yes[50.2]

Notes used in Appendix A

0.1) Abbreviations used for the Computer Language:

F	Fortran
F 77	Fortran 77
MS	MicroSoft
F IV	Fortran IV
C	program language "C"
HP Basic 4.0	Hewlett Packard Basic 4.0
F V	Fortran V
dBaseIV	Data Base Language
HPL	Hewlett Packard Language
HP-Special	Hewlett Packard Special

0.2) Abbreviations used for the Computer Type:

PC	Personal Computer
M	Mainframe
WS	Workstation
VAX	Vertual Address Extension
IBM	International Business Machine

0.3) for Equations see Table 1 - 12, Appendix C

0.4) for Algorithm to Solve Nonlinear Set of Equation see Table 13, Appendix C

0.5) Abbreviations used for the Name of Algorithm to Solve Nonlinear Set of Equation:

N - R	Newton - Raphson - Method
MNR	Modified Newton - Raphson Method
Lev - Mar	Levenberg - Marquardt Method
Gauss	Gaussian Elimination
Bro - Con	Brown - Conte Method
Beta	Beta Method by Newmark
N - Steff	Newton Method with Steffensen Acceleration
Sec - Met	Secant Method

1.1) Kajima General Ventilation Calculation Program

2.1) Calculation of Infiltration

2.2) under consideration

2.3) not so useful

4.1) Passive System Simulation Program / Multiroom Version 1

4.2) not in particular

4.3) integration of 1 E or 2 D

4.4) Transformed Newton Method for the System of Nonlinear Equations using Jacobian Matrix

4.5) under the revise for new version

5.1) still under development

5.2) by Dividing Them to Horizontal Equidistant Strips

5.3) Lineare Interpolation from CPBANK

5.4) Internal Reference Pressure Adjusted until Flow Errors Negligible

5.5) Not Fully Tested

5.6) Optional

5.7) after completing and testing

7.1) Infiltration and Ventilation

8.1) AIR-Calculation

9.1) Numerically Derived Jacobian-Matrix is inversed and Calculated Pressure Correction Vector is multiplied by 0.5 for Avoiding Oscillation

9.2) only in Japanese

10.1) Reference Pressures adjusted until Flow Errors Negligible

14.1) Simultaneous Heat, Moisture And Ventilation Predicting Program Multi Rooms

14.2) revised Newton - Raphson Method

16.1) Modified - Walton (NBS) Algorithm

16.2) not yet

16.3) not yet (used at users risk)

17.1) Model For Fluctuating Wind Pressure

19.1) alternate

20.1) Lineare interpolation between given points

20.2) Method with optimized Acceleration

22.1) Secant and u/L - Decomposition

28.1) Harmonic Analysis (Reference 1) and Lagrange Interpolation (Reference 2)

28.2) with some restrictions

29.1) Fortran Program to Calculate Air Infiltration in Buildings - May 1974

29.2) but a second program, named CP 46, is combined with pollution model (smoke concentration)

30.1) its applicability is very limited

32.1) Iterative technique using linear approximation to set of nonlinear equations including Q and P.

33.1) still under development

33.2) treated like large openings

33.3) calculated by CPCALC, calculation program, see "Fundamentals of the Multizone", Air Infiltration and Ventialtion Centre, Technical Note 29, May 1990

33.4) optimized Newton, Newton with given relaxation, Newton-Steffensen

36.1) It is intended that the program be compiled with the appropriate values of a few parameter statements to match the program to the problem.

38.1) still under development

38.2) still under development

39.1) total number of connections smaller than 200

40.1) 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).

40.2) 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

40.3) one to each attached region

41.1) Simplified Air Flow Model

46.1) Internal reference pressure adjusted until flow errors negligible

47.1) Internal references pressure adjusted until flow errors negligible

48.1) treated like large openings

48.2) calculated by CPCALC, calculation program, see "Fundamentals of the Multizone", Air Infiltration and Ventilation Centre, Technical Note 29, May 1990

48.3) optimized Newton, Newton with given relaxation, Newton-Steffenson

48.4) as soon as fully debugged

49.1) Equation to be specified by the user

49.2) available at the National Institute of Standards and Technology

50.1) Equation to be specified by the user

50.2) available at the National Institute of Standards and Technology

APPENDIX B

The authors and references of the computer programs

Model - Number :	1
Author :	Shin Hayakawa Building Environmental Engineering Department Kajima Institute of Construction Technology Kajima Corporation 2-19-21 Chofu-City, Tokyo Japan
References :	1. Hayakawa, S.; Togari, S.; Hioki, M.: "Air Flow Rate Variation of HVAC caused by Stack Effect and Opening a Window"; Third International Symposium on the Use of Computers for Environmental Engineering related to Building, pp 627-636, Banff, Canada, Mai 1978
Model - Number :	2
Author :	Hitoshi Yamazaki Department of Architecture Faculty of Engineering Oita University 700, Dan-no-haru Oita-shi, 870-11 Japan
References :	--
Model - Number :	3
Author :	Mitsuhiro Udagawa Department of Architecture Kogakuin University 1-24-2, Nishi-Shinjyuku Shinjyuku-ku, Tokyo Japan, 160
References :	1.Ishida, K.-I.; Udagawa, M.:"A Practical Method for Calculation of Room Temperature Variation Considering Natural Ventilation and Radiant Heat Exchange among Room Surfaces in Multi - Room Buildings"; Transactions of the Architectural Institute of Japan, Nov. 1987 2. Ishida, K.-I.; Udagawa, M.: "Validation of the Ventilation Net Work Model for the Estimation of Room Temperatures and Heat Load of Residential Buildings with Measured Data"; Transaction of the Architectural Institute of Japan, Oct. 1988 3. Ishida, K.-I.; Udagawa, M.: "Ventilation of Simulation Program for the Estimation of Thermal Performance of Residential Houses using the Data from the Year Round Monitoring"; CLIMA 2000, 1985

Model - Number : 4

Author :

Tetsuo Hayashi
Department of Thermal Energy System
Interdisciplinary Graduate School of
Engineering Sciences, Kyushu University
6 - 1 Kasuga-Kouen
Kasuga-Shi, Fukuoka-Ken, 816
Japan

References :

1. Hayashi, T.; Urano, Y.; Watanabe, T.; Ryu, Y.: "Passive System Simulation Program "PSSP" and its Applications", Proceedings of Building Energy Simulation Conference 1985, Seattle, USA

2. Hayashi, T.; Urano, Y.; Katayama, T.; Sugai, T.; Watanabe, T.; Shiotsuki, Y.; Ryu, Y.: "Prediction of Air Distribution in Multiroom Buildings"; Proceedings of the Roomvent-87 (Air Distribution in Ventilated Space), 1987, Stockholm, Sweden

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Model - Number : 5

Author :

Karoly Balazs
Hungarian Institute for Building Science (eti)
P.O.B. 71
XI. David F. u. 6.
Budapest 1113, Hungary

References : --

Model - Number : 6

Author :

Ian C. Ward
University of Sheffield
Dept. of Bldg. Science
Sheffield S10 2TN
United Kingdom

References : --

Model - Number :	7,8
Author :	Marian .B. Nantka Institute of Heating, Ventilating and Air Protection Silesian Technical University Pstrowski 5, Room 23 44 100 Gliwice, Poland
References :	1. "Effectiveness of Ventilation Functioning in Multi-Story Residential Houses"; (in polish; District Heating, Heating & Ventilation) No.6, pp 154, 1981 2. "A Numerical Method for Air - Change Rate of Buildings Calculated"; Recordings of the 5 th International Conference on HVAC, Czechoslovakia, Nov. 24-26, 1981 3. "Mathematical Method for Natural and Mechanical Air Flows Calculated" (in polish)
Model - Number :	9
Author :	Hiroyasu Okuyama Division of Environmental Technique Shimizu Corporation Institute of Technology 4-17-, Etchujima 3-chome, Koto-ku Tokyo, Japan
References :	1. Okuyama, H. : "Theoretical Study on the Thermal Network Model in Buildings"; (Doctorate) Waseda University, Tokyo, Dec. 1987 2. Okuyama, H. : "Network Numerical Analysis Method for Heat Transfer and Airflow in Buildings"; Proceedings of 17 th Symposium by the Committee of Building Heat Transfer in Building Environment, Comitees of Architectural Institute of Japan, Aug. 1987 3. Okuyama, H. : "A Computer Modelling Method of Building Airflow Network and The Solution of Non-linear Simultaneous Equations"; Annual Meeting Proceedings of Society of Heating Air-Conditioning and Sanitary Engineers of Japan, Oct. 1989, p 729, (Japanese)
Model - Number :	10
Author :	Servando Alvarez Dominguez Dpto. de Ingeneria Energetica y Fluidomecanica Escuela Tecnica Superior de Ingenieros Industriales Avda. Reina Mercedes E-4101 Sevilla Spain
References :	--

Model - Number :	11,12
Author :	Redwan Mounajer Centre Scientifique et Technique du Batiment Station de Recherche 84, Avenue Jean Jaures F-77420 Marne la Vallee Decex 2 France
References :	--

Model - Number :	13
Author :	Johnny Kronvall Dep. of Building Science Lund University P.O. Box 118 S-221 00 Lund, Sweden
References :	1. Kronvall, J.: "Air flow in Building Components"; Div of Building Technology, Lund Institute of Technology, Report TVBH - 1002, Lund, Sweden 1980

Model - Number :	14
Author :	Takao Tsuchiya Department of Architecture Faculty of Engineering Toyo University 2100 Kujirai Kawagoe-Shi, Saitama Japan
References :	--

Model - Number :	15
Author :	Katsumichi Nitta Department of Architecture Faculty of Technical Art Kyoto Kogei Sen-i University Kaido-machi, Gosho, Matsugasaki, Sakyo-ku, Kyoto-shi, 606 Japan
References :	--

Model - Number :	16
Author :	Martin Liddament Air Infiltration and Ventilation Centre University of Warwick Science Park Barclays Venture Centre Sir William Lyons Road Coventry CV4 7EZ Great Britain
References :	--
Model - Number :	17
Author :	Takashi Sasaki Department of Architecture Hokkaido University Nishi 8-chome, Kita 13-jou, Kitaku Sapporo, 006 Japan
References :	1. Sasaki, T; Hayashi, M.; Aratani, N.: "On the Ventilating Characteristics of the Space under the fluctuating Wind Pressure" Int. Conf. Roomvent 1987, Stockholm, Session 4a, pp 1-12 2. Sasaki, T; Aratani, N.: "Study on Change from Summer - Oriented Houses to Winter - Oriented Ones and their Ventilation" Bulletin of Faculty of Engineering, Hokkaido University No. 145, pp 125-151, Dec.1988 3. Saski, T; et al: "Der Lueftungszustand von der Luftschicht durch die Wind-Unruhe" Trans. AIJ (Architectural Institute of Japan) No. 372, Feb. 1987
Model - Number :	18
Author :	Hiroshi Matsumoto Toyohashi University of Technology Department of Regional Planning Tempakucho Toyohashi-shi, 440 Japan
References :	1. Matsumoto, H.; Nagatomo, M.; Yoshino, H.: " A Calculating Method for Predicting Air Pollution in Multi-celled Buildings"; Meeting of Tohoku branch of AIJ, 33-36, 1988 (in japanese)

Model - Number :	19
Author :	George Walton National Institute of Standards and Technology BR/A 313 Washington D.C. 20234 United States of Amerika
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Model - Number :	20
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APPENDIX C

Equations used in the computer programs

Nomenclature see Table 14

TABLE 1: Equations used for flow through cracks

1 A) $F = D \quad \Delta P^n$

1 B) $Q = D \quad \Delta P^n$

1 C) $\frac{Q}{3600} = \frac{D}{3600} \ \Delta P^{1/n}$

1 D) $\Delta P = a\ Q^2 + b\ Q$

1 E) $Q = C \ L \ \Delta P^n$

1 F) $F = K \ \Delta P^x$

1 G) $Q = C \ A \ \Delta P^n$

1 H) $\Delta P = \left(\frac{Q}{K\,L}\right)^n$

1 I) $\Delta P = 0.5\ L\ \rho\ Q^2$

1 J) $\Delta p = a\ F + b\ F^2$

1 K) $\Delta p = \varsigma\ \frac{\rho}{2} \left(\frac{Q}{A}\right)^n$

1 L) $F = \rho\ D\ \Delta p^n$ with $n = \frac{2}{3}$

1 M) $Q = K \ \Delta p^n$

TABLE 2: Equations used for flow through large openings

2 A) $$F = D \ \Delta P^n$$

2 B) $$Q = D \ \Delta P^n$$

2 C) $$\frac{Q}{3600} = \frac{D}{3600} \ \Delta P^{1/n}$$

2 D) $$Q = A \ C \left(\frac{2 \ \Delta P}{\rho} \right)^{1/2}$$

2 E) $$F = K \ \Delta P^x$$

2 F) $$Q = A \ (2 \ \Delta P)^{1/n} \ \sqrt{(1/\rho)}$$

2 G) $$\Delta P = S \ Q^2$$

2 H) $$\Delta p = a \ F + b \ F^2$$

2 I) $$\Delta p = \varsigma \ \frac{\rho}{2} \left(\frac{Q}{A} \right)^n$$

2 J) $$F = \rho \ D \ \Delta p^n \quad ; \text{with} \ n = \frac{2}{3}$$

2 K) $$Q = K \ \Delta p^n$$

2 L) $$F = \frac{2}{3} \ w \ C_d \ \Theta \sqrt{\rho \ [\ 2 \ g \ (\ \rho_1 - \rho_2 \ ) - b_t \ ]} \ \left| \ H - Zn \ \right|^{\frac{3}{2}}$$

TABLE 3: Equations used for flow through duct work

3 A) $$Q = C\,A \left[P_f - \rho_f\, g \left(H_r - H_f + \frac{H_i}{2} - H_s \right) - P_i + \rho_i\, g \left(H_s - \frac{H_i}{2} \right) \right]^n$$

3 B) $$Q = A \left(\frac{2}{\rho} \right)^{1/2} \sum_{i=1}^{m} \left(\frac{1}{k} \right)_j^{1/2} \Delta p^{1/2}$$

3 C) $$P - \frac{\rho}{2} v^2 (1 + \Sigma\, \varsigma) + \Delta P_{vE} - P_D = 0$$

3 D) $$\Delta P = \left[K + \frac{f_L}{D} \right] \frac{g}{H^2\, D^4\, \rho}\, Q^2$$

3 E) $$Q = A_{NET}\, (2\, \Delta P)^{1/n} \left(\frac{1}{\rho} \right)^{1/2} \left(\frac{\lambda\ l}{d} + \Sigma\, \varsigma \right)$$

3 F) $$F = \frac{\left(\dfrac{2\ \rho\ A^2}{f\ \ L/D + \Sigma\, C_0^2} \right)^{1/2}}{\Delta p}$$

3 G) $$Q = A \left(\frac{2\, \Delta p}{\rho\, \varsigma} \right)^{(1/n)}$$

3 H) $$\Delta p = \varsigma\, \frac{1}{2}\, \rho\, v^2$$

and : $$\Delta p = \frac{\lambda\ l}{d}\, \frac{1}{2}\, \rho\, v^2$$

3 I) $$F = A \left(\frac{2\, \rho\, \Delta p_K}{\left(\dfrac{\lambda\ L}{d} \right) + \Sigma\, \varsigma} \right)^{(1/2)}$$

3 J) $$\Delta p = C\, Q^2$$

TABLE 4: Equations used for fan flow characteristics

4 A) $Q = K_1 + K_2\,\Delta P + K_3\,\Delta P^2$

4 B) $\Delta P = K_1 + K_2\,Q + K_3\,Q^2$

4 C) $\Delta P = \Delta P_o - K_1\,Q - K_2\,Q^2$

4 D) $\Delta P = B\,n^2\,D^2 + \dfrac{Q^2}{A^2\,D^4}$

4 E) $\Delta P = f(Q_v)$

4 F) $\Delta p = K_0 + K_1\,F + K_2\,F^2 + K_3\,F^3$

4 G) $\Delta p_t = K_1 + K_2\,Q + K_3\,Q^2 + K_4\,Q^3$

4 H) $\Delta p = C_1 - (\,C_2\,Q^2)$

TABLE 5: Equations used for wind pressure

5 A) $\Delta P = \dfrac{\rho}{2}\,v^2$

5 B) $\Delta P = C\,\dfrac{\rho_o}{2}\,v^2$

5 C) $\Delta P = C\,\dfrac{\rho}{2}\,v_o^2$

5 D) $\Delta P = C\,\dfrac{\rho}{2}\,v\,H^2$

5 E) $\Delta P = \dfrac{\rho}{2}\,v^2$

with: $v = v_O\,2334\,[1 + 2.8\log(H + 4.75)]$

5 F) $\Delta p = K\,v^2\,cp$; with : cp are input

5 G) $p_{wind} = cp\,\dfrac{1}{2}\,\rho\,v^2$

5 H) $\Delta p = cp\,\Delta p_{dyn}$

TABLE 6: Equations used for thermal buoyancy

6 A) $\Delta P = \rho\ g\ \Delta H$

6 B) $\Delta P = (\rho_o - \rho_i)\ g\ (H - H_o)$

6 C) $\Delta P = 3462\ (H - H_o) \left(\frac{1}{T_o} - \frac{1}{T_i} \right)$

6 D) $\Delta P = (\rho_o - \rho_i)\ g\ H$

6 E) $\Delta P = (\rho_o - \rho_i)\ g\ H\ (X - 0.5 - N/2)\ b + c$

6 F) $Q = (C_D\ A/n) \left(\Delta\ \Theta\ g\ \frac{H}{\overline{\Theta}} \right)^{1/2}$

6 G) $\Delta P = \rho_o \left(\frac{T_i - T_o}{T_i\ T_o} \right) T_o\ g\ H$

6 H) $\Delta p = \rho\ g\ 273\ (h - h_0) \left(\frac{1}{T_0} - \frac{t}{T_i} \right)$

6 I) $\Delta p_z = \Delta\ \rho\ g\ z$

6 J) $\Delta p = (\ p_i - \rho_i\ g\ h_i\ ) - (\ p_j - \rho_j\ g\ h_j\ )$

6 K) $\Delta p = \Delta\rho\ g\ \Delta H$

TABLE 7: Equations used for outside pressure fluctuations

7 A) $(\Delta \overline{P'^2})^{0.5} = 0.5\ (\overline{P_o'^2})^{0.5}$

7 B) $Q_v = 1/2\ A_{NET}\ (0.001\ v^2 + 0.0035\ \ H\ \ \Delta\ T + 0.01)^{1/2}$

TABLE 8: Equations used for circulation flow on large openings

8 A) $Q_x = C_d\ A_x \left(\frac{2}{\rho}\ \Delta p \right)^{0.5}$

8 B) $Q = K\ \Delta p^{0.5}$; with : $\Delta p = \Delta\rho\ g\ h$

8 C) $\Delta\ F = F_{O,ZN} - F_{ZN,H}$

TABLE 9: Equations used for single sided ventilation

no equations were specified

TABLE 10: Equations used for cross ventilation

10 A) $Q = K\,\Delta p^{0.67}$

TABLE 11: Equations used for pressure coefficient

11 A) $cp = 0.75 - 1.05\,\frac{Q}{90}$ if $Q \leq 90°$

$cp = -0.45 + 0.15\,\frac{Q}{90}$ if $Q > 90°$

$==> \quad \Delta p_{wind} = \frac{1}{2}\,\rho\,cp\,v^2$

11 B) $c_w = 0.75$ if $b = 0 - 30°$

$c_w = -0.01667\,b + 1.25$ if $b = 30 - 75°$

$c_w = -0.02667\,b + 2.0$ if $b = 75 - 90°$

$c_w = -0.4$ if $b = 90 - 180°$

11 C) $cp_{wind} = 1$ $cp_{lee} = -0.3$

TABLE 12: Equations used for temperature gradient

12 A) $Q = \int_{H_1}^{H_2} D\,\Delta p\,\left|\,\Delta p\,\right|^{\frac{1}{n}-1}$

12 B) $\frac{dp}{dz} = -\frac{g\,p_o\,273}{w_z + T_{zo}}$

12 C) $p = \frac{p_{ref}}{R\,(T_{ref} - \lambda_t\,H)}$

and: $dp = -\rho\,g\,dH$

12 D) $T_z = a\,z + T_{zo}$

and: $p_z = g\int_0^h p(z)\,dz$

TABLE 13: Algorithm to solve the nonlinear set of equations

13 A) $$P_{j+1} = P_j \pm \left(\frac{Q_j}{C_j A_j} \right)^{nj}$$

13 B) $$P_{j+1} = P_j - \frac{\Sigma Q}{\Sigma Q'}$$

13 C) $$CR = \frac{\Sigma D \, \Delta P^{1/n}}{\Sigma \left| \frac{D}{n} \Delta P^{((1/n)-1)} \right|}$$

13 D) $$\Sigma F = O$$

13 E) $$P_{j+1} = P_j - \text{Correction}$$

13 F) $$\text{Minimize over } P \left(\sum_{i=1}^{N} fi^2 (P) \right)$$

with: $$fi (P) = \sum_{j=1;i\neq j}^{N} L_{ij}$$

13 G) $$[A] [\Delta p] = [q]$$

13 H) $$P_{n+1} = P_n - \lambda \frac{f(p)}{J(p)}$$

13 I) $$\sum_i Q_i = 0$$

TABLE 14: Nomenclature

Symbol	Description	Unit	Symbol	Description	Unit
A	area	m^2	a,b,c...	coefficient	--
			b_t	turbulent pressure gradient	Pa/m
B	constant	--	cp	surface pressure coefficient	--
C	crack flow coefficient	$m^3/m\ h\ Pa^n$	d	diameter	m
D	flow coefficient	$m^3/h\ Pa^n$	f	friction factor	--
E	effective leakage area	kg/h	f(...)	function of	--
F	mass flow rate	kg/h	g	gravity	m/s^2
H	height	m			
K	constant	--	l	duct length	m
L	crack length	m	n	flow exponent	--
P	pressure	Pa			
Q	volume flow rate	m^3/h	t	relative temperature	°C
R	gas constant	J/kg K	v	velocity	m/s
S	resistance	$h\ Pa/m^3$	w	wind speed	m/s
T	absolute temperature	K			
Zn	position of a neutral plane	m	z	depth of crack	m

Greek letters			**Subscripts**		
Δ	difference	--			
$\sum$	Summation	--	d	discharge	--
Θ	absolute temperature	K	f,i,r,s	locations in the duct system	--
λ	friction factor	--	i	inside	--
λ_t	temperature gradient	K/m			
ν	viscosity	m^2/s	j	iteration step	--
ρ	air density	kg/m^3	j+1	iteration step + 1	--
ς	fitting loss factor	--			
μ	viscosity of air	m^2/s	NET	inside	--
			o	outside	--
			ref	reference	--
			s	stack	--
			t	total	--
			0	reference	--

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