

**INFILTRATION AND INTERZONE AIRFLOW
MODELING FOR BUILDING
ENERGY ANALYSIS**

By

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1987

**Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1992**

Thesis
1992
P426i

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PREFACE

An infiltration and interzone airflow model was developed for use in building energy analysis. The model was implemented into the Building Loads Analysis and System Thermodynamics (BLAST) program. The theory, algorithms, solution method and computer program for modeling a variety of airflow elements such as cracks, doorways, ducts, and fans are described. Potential applications of the model are demonstrated with examples in the areas of attic ventilation, ventilative cooling of structures, and prediction of thermal comfort.

A variety of tests indicated that the detailed analysis of building airflows is a practical possibility given adequate knowledge of building surface pressure coefficients and element flow parameters. The yearlong simulation of building airflow networks on an hourly basis for use in energy analysis is also feasible. Implementation of the model into the BLAST program has increased the usefulness of BLAST, particularly for cases where ventilation and/or interzone airflows have a significant effect on the thermal balance.

I would like to express my sincere gratitude and appreciation to my major advisor Dr. Jeffrey. D. Spitler for his intelligent guidance, inspiration, and constant encouragement throughout this research work. I am also thankful to Dr. David. G. Lilley and Dr. Ronald. D. Delahoussaye for serving as members of my advisory committee and providing valuable suggestions.

This project has been funded by the University Center for Energy Research at Oklahoma State University. Their financial support in the form of research assistantship is sincerely appreciated.

Many of the concepts and ideas used in this project were previously used by the Airnet model of Mr. George N. Walton of the National Institute of Standards and Technology. Special thanks are due to Mr. Walton for the long discussions and useful suggestions during the course of this project.

To all my wonderful colleagues in the HVAC research group, school and college teachers, relatives and friends, I extend my sincere thanks.

Finally, I owe a deep sense of gratitude to my parents, Mr. Simhasen and Mrs. Sulochanasen whose love, encouragement, guidance, and sacrifice have made it possible for me to come this far in life. Special thanks are also due to my brothers Sumansen and Subodhsen for their love, friendship, and moral support.

This thesis is dedicated to my parents.

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CHAPTER I

INTRODUCTION

Overview

Airflow modeling for estimation of infiltration and interzone airflows has been a largely ignored aspect in the process of analysis and design of Heating, Ventilating and Air Conditioning (HVAC) systems for buildings. When thermal comfort is being evaluated to determine if mechanical air conditioning is required, the building airflows and resulting convection heat transfer play an important role because of the significant amount of energy associated with these flows.

Infiltration, ventilation and interzone airflows constitute three major types of air exchange in buildings. Practically no building is perfectly airtight. There is always a considerable amount of air leakage through the cracks around the doors and windows, through the construction joints, and through the building fabric itself. Infiltration is the terminology used for the unintentional flow of air from the ambient through the distributed leakage paths in buildings, whereas ventilative airflow is effected intentionally either by powered or unpowered outdoor airflow through open windows, doors, and other intentional openings in buildings. Interzone airflow is caused by pressure difference arising from wind and by buoyant forces occurring due to difference in air density of coupled zones.

The energy associated with heating or cooling of infiltrated outdoor air is a significant space air conditioning load. It is necessary to know the magnitude of these infiltration and building airflows in order to properly size the equipment and assure proper control of indoor air contaminant level. Due to difficulties associated with calculating

infiltration flowrates, the rule-of-thumb practice in the air conditioning industry is to estimate infiltration flowrates using a presumed number of air changes per hour (ACH). Though this method is simple to apply and could be a useful check, it has no physical basis.

The next level of detail in infiltration calculations is to make use of available statistical fits which are developed based on long-term infiltration rate measurement data for specific building sites. ASHRAE Handbook of Fundamentals (ASHRAE, 1985) provides a simplified correlation infiltration equation which makes use of wind speed V (m/s), outdoor-indoor temperature difference ΔT ($^{\circ}\text{C}$), and empirical regression constants which are derived from field measurements. The equation is as follows:

$$\text{ACH} = A + B \cdot \Delta T + C \cdot V \quad [1.1]$$

However, it has been reported that most of the time these correlations are only moderately successful and they may not be appropriate for inclusion in computer simulations for building energy analysis.

The more accurate and rational approach to infiltration calculations is through a detailed survey of the sources of airflow followed by an evaluation of their magnitudes at each time step, which is performed separately for each conceivable flow passage connecting a zone to another zone or to ambient conditions. The more detailed modeling can be possible with the analysis of flow domain using numerical solution of governing partial differential equations pertaining to the conservation of mass, energy, momentum and turbulence. These methods are very useful in accurately predicting airflow under complex building geometry, boundary conditions and air mixing conditions. But this approach demands too many details and has limited practical applications in energy analysis where, most frequently, yearlong hourly simulations are performed.

An approach of intermediate level of complexity is to analyze building air movement as a simplified nodal network consisting of nodes and links. The discrete volumes of air,

like zones, ambient conditions, connecting duct points, etc., are represented by nodes. Internode connections, called links, represent distributed linkage paths, like cracks, doors, windows, ducts, fans, etc., through which air will flow if subjected to some pressure difference caused by wind or buoyancy effects. Numerical solution techniques can then be used to solve these networks on the basis of mass balance corresponding to any particular set of environmental conditions.

Although very simple flow networks may be studied analytically, real buildings require a systematic approach using computers for analysis. Various models and numerical methods have been developed to estimate the infiltration and interzone airflows in the buildings. The recent models of Clarke (1985) and Walton (1989) are based on the idea that a nonlinear relationship exists between airflow through a passage and the pressure drop across it. These pressure differences arise due to wind and thermal forces. The conservation of mass at each node gives a set of simultaneous nonlinear equations with various unknown node pressures as variables, which are then solved iteratively for these variables. When these node pressures are known on each side of an element, the airflow through that element can be calculated.

As generally very little information is known about flow characteristics, distribution, and size of these numerous openings and passages in the buildings, the mathematical representation of the airflows through the openings is quite complicated unless considerable amount of simplification is made. The Airnet model of Walton (1989) has a rigorous approach in modeling various airflow passages like construction cracks, doorways, ducts, and fans. Airnet uses Newton's method (Newton-Raphson method) combined with the Steffensen iteration (Conte and de Boor, 1972) to solve the nonlinear airflow equations. The Steffensen iteration helps to accelerate convergence of the solution. It also uses the skyline solution process, a sparse matrix solution method (Dhatt et al. 1984) which reduces both the storage and execution time. Airnet demonstrates the practical

possibility of solving these airflow networks and successfully modeling the building airflows.

The wind pressure calculation at the inlet and outlet of various openings in the buildings, mathematical representation of airflow passages, and finally providing an efficient method for calculation of airflows through the network are the important aspects of modeling building airflows. The knowledge of building surface pressure distribution is essential in order to calculate infiltrations. Research work has been done in this area by Vickery et al. (1983), Wiren (1985), Swami and Chandra (1988) and others. Wind angle, building geometry and terrain significantly influence values of surface pressure coefficient (C_p). Chapter 14 of the ASHRAE Handbook of Fundamentals (ASHRAE, 1989) discusses surface pressure distribution on buildings for various scenarios. Accurate evaluation of C_p can only be possible if extensive wind tunnel tests of a model of the specific building and the surrounding site are performed. However, reasonable estimates can be made by using suitable correlations and also by making use of existing wind tunnel test data of similar sites. Swami and Chandra (1988) describe models to estimate the wind pressure distribution on the external surface of a building. Their work is based on correlated pressure coefficient data for different building shapes from a world wide database. Though much of this database is limited to simple building shapes, this is the best data presently available. An alternative to this is to numerically calculate pressure coefficient data using computational fluid dynamics techniques. But the feasibility of using CFD for this purpose has not yet been established.

With the increased concern about the ozone layer recently, it is likely that there will be further pressure to justify the installation of mechanical air conditioning systems. Apart from this, analysis of thermal comfort and indoor air quality in residences, offices, and other indoor environments is a growing concern. Furthermore, in recent years interest in attic ventilation and ventilative cooling of buildings has increased due to rising energy

costs. In such situations, infiltration and interzone airflow modeling are definitely of great interest in the air conditioning industry.

Objectives

The primary objective of this work is to develop an infiltration and interzone airflow model (hereafter referred to as the Network model) and implement this model along with the best available pressure distribution model into the Building Loads Analysis and System Thermodynamics (BLAST) program [BLAST Support Office, 1986]. BLAST is a comprehensive hourly building energy simulation program developed by the U.S. Army Construction Engineering Research Laboratory (USACERL). The current BLAST program does not have the capability to calculate wind driven ventilation and has no features to accurately predict interzone mixing, rather users must schedule interzone mixing. The implementation of the Network model will enable BLAST to compute hourly infiltration flows and interzone air mixing rather than requiring users to specify them. Thereby increase the usefulness of the BLAST program particularly for cases where ventilation and/or interzone airflows have a significant effect on the thermal balance.

BLAST works on an hour-by-hour basis, and hence a significant amount of CPU time is required to perform a simulation for a period of one year. So the Network model must be tested in detail for its reliability, robustness, accuracy, and computational time requirements before it can be implemented into the BLAST program.

The main elements in infiltration and interzone airflow modeling are crack and doorway models. Apart from these, the duct and fan airflow models will be developed for use in the analysis of duct airflows in HVAC systems.

Application of the Network model will be demonstrated with examples in the areas of attic ventilation, ventilative cooling of structures, and prediction of thermal comfort.

CHAPTER II

LITERATURE REVIEW

Most of the work related to infiltration and interzone airflow has an emphasis on three major areas: wind and building surface pressure distribution, formulation of airflows in buildings through various flow elements and solution methods for airflow networks. This literature review is organized by these three areas.

Wind and Surface Pressure Distribution

Wind serves as a major driving force for building infiltration. However it is a difficult task to quantify influence of wind on building airflows, because surrounding terrain and shielding conditions have significant influence on wind behavior. If the external pressure distribution is known with the size, shape and location of both external and internal openings, then the building airflows can be computed based on established procedures. Vickery et al. (1983) have attempted to evaluate the accuracy of internal flow estimates deduced from the external pressure distribution measured on scale building models. They have also presented a database for external pressure distribution on low-rise buildings.

Allard and Herlin (1989) have both analytically and numerically studied wind induced ventilation in buildings. Their paper emphasizes the influence of wind effect alone and its combination with stack effect and mechanical exhaust system on infiltration. Swami and Chandra (1988) have presented a brief structured procedure for calculating wind-driven natural ventilation.

A literature review prepared by Chandra et al. (1982) contains a summary of each major work done in this area, a matrix relating the subject matter to various aspects of ventilative cooling and a compilation of airflow diagrams observed in wind tunnel studies.

Local Wind Speed

Buildings are usually located at significant distances from nearest weather recording stations. In such cases corrections need to be made to the weather station wind data to account for difference in terrain. Wind engineers have developed classification of terrain ranging from open ocean front to center of large cities. Liddament (1988) describes a typical correlation equation for correcting reference terrain wind data for both the difference in height between measurement level and building height, and for intervening terrain roughness. The correlation equation is:

$$V = V' \left(\frac{a}{a'} \right) \frac{(H/10)^b}{(H'/10)^{b'}} \quad [2.1]$$

V = building terrain wind speed at height H meters above ground (m/s)

V' = wind speed in the referenced terrain at height H' meters above ground (m/s)

a, b = terrain constants of the building terrain

a', b' = terrain constants of the reference terrain

Liddament (1988) also presents a brief listing of these terrain constants for a variety of terrains.

Aynsley (1989) uses a slightly different version of the above powerlaw relation for terrain wind speed calculations. He has discussed two examples in his paper and demonstrated how these wind speed corrections are made.

Surface Pressure Distribution

Based on Bernoulli's equation, the wind pressure P (Pa) acting on a building surface can be estimated from on-site wind speed V (m/s) and empirical surface pressure coefficient (C_p) as follows:

$$P = C_p \frac{\rho V^2}{2} \quad [2.2]$$

where ρ is air density (kg/m^3).

Knowledge of building surface pressure distribution is essential in building airflow calculations. Pressure coefficients at various locations on building surfaces are influenced by pattern of flow around the building, building shape and proportions, surroundings, wind incidence angle, topographic features, and vegetation. These coefficients are rarely known to a fine degree of accuracy unless extensive wind tunnel tests are conducted on a scale model of the building and its surroundings.

Chapter 14 of the ASHRAE Handbook of Fundamentals (ASHRAE, 1989) contains details for estimating surface pressure coefficients and has discussed various examples of surface pressure distribution on buildings.

Akins et al. (1979) conducted wind tunnel studies for pressure coefficients on a series of flat-roofed rectangular building models made of plexiglass and fitted with pressure taps at 272 locations on each building (60 on each vertical face and 32 on the roof). These models were tested making use of a digital data acquisition system on the industrial aerodynamics wind tunnel of the Fluid Dynamics and Diffusion Laboratory, Colorado State University. Four boundary layers were used in their wind tunnel study, a feature which allows more detailed examination of the effects of building geometry and incident flow property on mean wind pressure.

Swami and Chandra (1988) have attempted to develop several correlations for C_p using a worldwide database on surface pressure distribution from different investigators for use in natural ventilation calculations for low rise and high rise rectangular buildings.

Surface pressure coefficients are referenced by different investigators based on wind speeds at different heights. To facilitate the curve fitting and to achieve uniformity, Swami and Chandra in their study have normalized the C_p data with respect to the C_p at zero incidence angle referenced to building height.

In their analysis, Swami and Chandra found that average surface pressure coefficients for low-rise buildings were adequate. They have reported that the error introduced by using average rather than local surface pressure coefficients for low-rise buildings was about 5.0%. They have developed a nonlinear regression equation for average C_p with wind incidence angle and building side ratio (i.e., ratio of width of wall under consideration to width of adjacent wall) as variables. They have suggested that a uniform value of 0.60 may be chosen to represent C_p at zero incidence angle for all types of low rise buildings which represent the average of all C_p data at zero incidence wind angle.

In the case of high-rise buildings, pressure coefficient variations along the height of building are relatively large. Therefore regression equations for local rather than average surface pressure coefficient are required. Swami and Chandra have included horizontal and vertical coordinates of the points on the wall as well as wind incidence angle and building side ratio in their regression equation for high rise buildings.

Generally, most buildings are not of simple rectangular shapes. Buildings may be of "L" or "U" shapes, or even more complex shapes due to presence of garages, wingwalls, porches etc. Since measured data for pressure coefficients are unavailable for these complex common building shapes so far, some educated guess work for computing average wall C_p for buildings in such cases is essential. Swami and Chandra have discussed commonsense guidelines to handle such situations.

Swami and Chandra found inadequate data for roofs to see any systematic effect of roof slopes on pressure coefficients. So the correlations recommended by them do not include roof slope as a variable. Additional research in this area and systematic wind tunnel

tests on different types of regular complex building shapes is desirable to accurately analyze a variety of such situations.

Element Flow Formulation

Airflow network models employ airflow and mass balance equations. Mathematical characterization of airflow paths is an important aspect in this process. These leakage equations are employed to represent flow through cracks, doors, and windows connecting different zones in a building. In a paper on airtightness of office-buildings, Persily and Grot (1985) discuss the relationship between envelope airtightness and air exchange rates. They also discuss the building pressurization measurements and tracer gas measurements of air exchange rates in office buildings.

So far, many models pertaining to building airflow or smoke control analysis have been developed. The key features, limitations and assumptions made in the existing smoke control models have been reviewed by Said (1988). Said in his paper has discussed various smoke control models and has presented a brief comparison of the features and capabilities of these models. The more sophisticated models take into account all the driving forces governing smoke movement, including effects of heat release from a fire in terms of buoyancy and thermal expansion of hot gases.

An ASHRAE publication by Klote and Fothergill (1983) has sample simulations and complete listing of the computer coding for NBS/USA model. Klote and Fothergill also discuss driving forces governing smoke movement, principles of smoke control, and the parameters necessary for design of smoke control systems. Apart from buoyancy and wind pressure, energy released by a fire may lead to the spread of smoke due to expansion of gases associated with combustion. Neglecting mass of fuel involved in combustion phenomena, the volumetric flowrates can be expressed as ratios of absolute temperatures of gases. For a smoke temperature of 700 °C, the ratio of volumetric flows would be 3.32 (Klote and Fothergill, 1983) which means the combustion gases are expanded to more than

three times of original volume. The neglect of such an effect will lead to under-prediction of the smoke movement in a building.

Major contributors to infiltration and interzone airflow modeling for building energy analysis are Clarke (1985) and Walton (1989). Their building airflow models are based on the principle that there exists a simple nonlinear relationship between flow through an opening and relative pressure difference across it. The Airnet model of Walton (1989) is a stand-alone type model intended for analysis of only building airflows. The model separates the evaluation of wind pressures from the airflow calculations and it has no features for computing building airflows on an hour-by-hour basis for use in yearlong building energy analysis. However, Airnet has a rigorous approach in modeling a variety of major airflow passages.

The flow area of large openings such as windows, ducts, doorways etc., can be calculated easily. But computation of flow area for some obvious air leakage paths in buildings, such as cracks around closed doors, elevator doors, windows and grills is quite difficult. These leakage areas are dependent on workmanship, i.e., how well the door is fitted, or how well the weather stripping is installed. A door that is 0.9 x 2.1m with an average crack width of 3.2mm has a leakage area of 0.02m². However if the door is installed with 19mm undercut, the leakage area will go as high as 0.03m² (Klote and Fothergill, 1983). This is a significant difference, especially when the pressure difference and flow rates involved are high.

Crack Airflow

Most of the researchers have modeled flow through infiltration openings using a powerlaw relationship of the form :

$$m = C \sqrt{\rho} (\Delta P)^x \quad [2.3]$$

where C is flow coefficient, ρ is air density and x is flow exponent which depends on flow characteristics.

From hydrodynamics laws, the character of flow through a leakage path changes as the pressure across the path changes. At lower pressures, the flow is dominated by viscous forces, and at higher pressures it is dominated by inertia force. So at lower pressure differential across a leakage path, the flow is laminar and is proportional to the pressure drop, and at higher pressure differential the flow is turbulent and is proportional to the square root of the pressure drop. At intermediate pressure drop the flow behavior is a combination of these effects. The geometry of a crack has a significant influence on the pressure range in which the flow behavior changes.

Though a simple powerlaw relationship can be used to describe the relationship between flow and pressure drop for a wide range of crack geometries, it has been documented by Etheridge (1977) that it lacks generality because it is not dimensionally homogeneous. In the light of this, Baker et al. (1987) have suggested a quadratic relationship (Equation 2.4) to replace the ubiquitous powerlaw as a practical fit to building pressurization data. They also have reported that a quadratic flow relationship matches the experimental data better than a powerlaw relationship. However before any one of these models can be used extensively, their accuracy and range of validity need to be established.

$$\Delta P = A \cdot \dot{Q} + B \cdot \dot{Q}^2 \quad [2.4]$$

where \dot{Q} is the volumetric flow rate, ΔP is the pressure drop across the opening, and A and B are constants having some correlation with crack dimensions.

Many researchers have made efforts to quantify crack flow behavior and the characteristics of the leakage paths. Sherman and Grimsrud (1980) have proposed effective leakage area as an appropriate parameter for characterizing infiltration airflow. Effective

leakage area data for a variety of leakage paths like window and door cracks, ventilators, etc., can be found in Dick (1950).

The concept of effective airflow element is very useful for simplifying building airflow networks. Analogous to the flow of current through a system of resistances in DC electricity, flow paths in an airflow network system can be in parallel or in series, or in a combination of parallel and series paths. The effective flow element is a single flow element that results in the same flow on a system when it is subjected to the same pressure difference over the total system of flow paths. These relationships are analogous to those of electricity.

Klote and Fothergill (1983) and Walton (1989) have discussed this effective flow element concept. Klote & Fothergill (1983) have discussed this on the basis of flow area, whereas Walton has discussed this on the basis of flow coefficients. However, both of these discussions are conceptually the same.

Doorway Airflow

Analysis of airflow through a doorway tends to be more complex because of the possibility of flows in the opposite directions in different parts of the doorway. The doorways can be modeled in two ways. One way is by equivalent multiple powerlaw element model dividing the doorway opening into several smaller openings having the same cross sectional area but configured to properly account for the magnitude and direction of airflows at different heights in the opening (multiple opening approach). Another approach is to consider doorway as a single airflow element accounting for flow over the entire opening; however, in this case, neutral plane height, flow directions and possibilities of two-way airflow are taken into consideration. Walton (1989) has reported that the single airflow element doorway model converges to solution faster than the equivalent multiple opening model.

Barakat (1987) has reviewed the research work on heat transfer through doorways in buildings and has discussed the parameters governing this phenomena. Convection through doorways is supposed to be a major mechanism of heat transfer from one zone to another zone of a building. Brown and Solvason (1962) have carried out an extensive experimental study of natural convection through openings in vertical partitions for examining buoyancy driven airflows across large openings such as doorways. They have theoretically described the convective heat transfer process across openings in vertical partitions with a dimensionless correlation using the Nusselt number (Nu_H), the Grashof number (Gr_H), and the Prandtl number (Pr). Where the characteristic length is the opening height. The correlation equation provided by them is as follows:

$$Nu_H = \frac{C_D}{3} * Gr_H^a * Pr^b \quad [2.5]$$

where the exponent a on the Grashof number is approximately 0.5 and the exponent b on the Prandtl number is 1.0. The discharge coefficient C_D is in the range of 0.6 to 1.0.

Brown and Solvason conducted experiments to analyze airflow through a single rectangular opening at the center of a partition between two large test chambers. Each test chamber was 2.44m square and 1.22m long. The experiments were conducted for opening sizes of 0.152 x 0.152m, 0.152 x 0.305m, 0.229 x 0.229m, and 0.305 x 0.305m with air temperature difference ranging from 8.3 to 47.2 °C. They observed that their experimental results were in good agreement with the theory and validate the correlation.

Further, various ratios of partition thickness to opening height (t/H) ranging from 0.19 to 0.75 were also tested. Brown and Solvason observed a remarkable influence of t/H ratio on heat transfer rate for $Gr_H \leq 10^7$ and for t/H ranging from 0.38 to 0.75. But for t/H in the range of 0.19 to 0.38 and Grashof number between 10^7 and 10^8 , the influence was very little.

Duct Airflow

ASHRAE Handbook of Fundamentals (ASHRAE, 1989, Chapter 32) has a detailed account of principles of airflow in ducts and pipes. Walton (1989) has discussed the algorithms used in modeling duct airflow. The analysis is based on Bernoulli's equation. Total head loss in a duct is the sum of frictional losses in the duct and dynamic losses due to the duct fittings. Frictional losses can be calculated by using the Darcy-Weisbach equation. The friction factor in the Darcy-Weisbach equation may be computed by Colebrook's equation.

$$\frac{1}{\sqrt{f}} = -2 \log \left[\frac{\epsilon}{3.7 D_h} + \frac{2.51}{\text{Re} \sqrt{f}} \right] \quad [2.6]$$

ϵ = absolute roughness factor of the duct material (m)

D_h = hydraulic diameter of duct (m)

Re = Reynolds number

This is a nonlinear equation and can not be solved explicitly. It needs some iterative method for solution. Newtons method or any other nonlinear equation solution method may be used for this purpose.

As an alternative to Colebrook's equation, ASHRAE Handbook of Fundamentals (ASHRAE, 1989, Page 32.5) gives the following simplified explicit equation called Altshul's modified equation for computing friction factor.

$$f' = 0.11 \left(\frac{\epsilon}{D_h} + \frac{68}{\text{Re}} \right)^{\frac{1}{4}} \quad [2.7a]$$

$$\text{If } f' \geq 0.018, \text{ then } f = f' \quad [2.7b]$$

$$\text{If } f' < 0.018, \text{ then } f = 0.85 f' + 0.0028 \quad [2.7c]$$

ASHRAE reports that the values of the friction factors obtained by the above explicit equation are within 1.6% of those obtained by Colebrook's equation.

A listing of surface roughness factor for a variety of duct materials and fabrication, and the dynamic pressure loss coefficient for different resistances (e.g., bends, transitions, junctions, etc.) can be found in Chapter 6 of the Applied Fluid Dynamics Handbook (Blevins, 1984).

Fan Airflow

ASHRAE Equipment Handbook (ASHRAE, 1983, Chapter 3) describes the fan laws and theory of fan induced airflows. Flow through a fan can be modeled in two ways: using a detailed fan performance curve represented by a cubic polynomial equation, or on the basis of an assumption of constant power delivery to air stream by fan. Osborne (1977) discusses airflow through fans based on their performance curve fitted with one or more cubic polynomials of the form:

$$\Delta P = C_1 + C_2 \dot{m} + C_3 \dot{m}^2 + C_4 \dot{m}^3 \quad [2.8]$$

The above curve relates total pressure rise (ΔP) to airflow rate (\dot{m}) for a given fan speed and air density. This is a detailed fan model requiring many input parameters.

Walton (1989) discusses a simple fan model applicable for an assumption of constant operating conditions whose basic equation is as follows:

$$W = \frac{\dot{m} * \Delta P}{\rho} \quad [2.9]$$

W = fan power (W)

\dot{m} = mass flow rate (kg/s)

ρ = air density (kg/m³)

ΔP = total pressure rise across the fan (Pa)

In the case of detailed fan modeling, a fan performance curve may have points of contraflexure making it possible to have three different flow rates at certain fan pressures. It is general practice to avoid operating fan in those regions. So fans have to be modeled only in the region of performance curve that does not contain the points of contraflexure, and it is necessary to see that the airflow network does not permit the operation of fans in those regions.

Network Solution Method

Mass balance equations are the basic equations governing flows in an airflow network.

$$\Sigma m_{in} = \Sigma m_{out} \quad [2.10]$$

By applying the law of conservation of mass at each node a set of simultaneous nonlinear flow equations are obtained which must be solved iteratively for nodal pressures. The important point here is the reliability of method of solving these equations. The most reliable method is the one which converges rapidly to the correct solution. Byrne and Hall (1973) and Jeppson (1976) have discussed various methods of solving nonlinear equations and techniques used for solution convergence and acceleration.

Analysis of airflow networks is very similar to that of pipe flow networks. The paper by Isaccs and Mills (1980) discusses a solution method based on linear theory for junction heads in pipe flow networks. Wood and Rayes (1981) have presented principal algorithms for use in piping systems and systems containing other common hydraulic components. Wood and Rayes have examined the reliability of these algorithms by solving numerous pipe flow problems and have documented the comparison of several algorithms. Klote and Fothergill (1983) use an individual node head adjustment algorithm, whereas Walton (1989) uses a simultaneous node adjustment algorithm coupled with the Steffensen

iteration for applying corrections in Newton's method. This he does to prevent oscillating pressure corrections.

Among all nonlinear solution methods, Newton's method is the most popular one. It can be applied in many diverse situations with a combination of suitable convergence and acceleration techniques.

Newton's method begins with an estimate x_0 of solution and then defines inductively:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (n \geq 0) \quad [2.11]$$

This initial estimate x_0 is important. With poor starting points, Newton's method may take many iterations or may not converge at all. Walton (1989) does the initialization assuming linear flow relationship between airflow and corresponding pressure differential.

In many cases, there are instances of slow convergence with oscillating corrections in the iterative solution process. In order to ensure stability of the solution procedure and to promote convergence rate, Demuren and Ideriah (1986) use a constant under-relaxation factor ($\alpha = 0.5$) to prevent the oscillating corrections such that:

$$P_{n+1} = \alpha P_n' + (1 - \alpha) P_n \quad [2.12]$$

P_{n+1} = new value of the current iteration with relaxation

P_n' = new value of the current iteration without relaxation

P_n = value of P_n' at the previous iteration

To overcome the problem of oscillating corrections, Walton (1989) does the extrapolation of corrections to an assumed solution as follows:

$$P_{n+1} = P_n - \frac{C_{NEW}}{(1 - r)} \quad \text{where } r = \frac{C_{NEW}}{C_{OLD}} \quad [2.13]$$

C_{NEW} = recent pressure correction

C_{OLD} = old pressure correction

These extrapolated values of node pressures are used in the Newton's next iteration. This method is similar to the Steffensen iteration (Conte and de Boor, 1972) which is used with ordinary fixed-point iteration for solving individual nonlinear equations. Walton (1989) has reported that, by limiting the application of this method to cases where r is less than some value (such as -0.5), it will not interfere with the rapid convergence of the solution.

Matrix of partial derivatives (also called Jacobian Matrix) which is used in solving a set of nonlinear equations in Newton's method is usually sparse. It is not necessary to allocate any space for those locations whose values are zero in a matrix. Pissanetzky (1984) and Dhatt et al. (1984) have detailed discussion on techniques for storage and solution of the sparse matrices. These sparse matrix techniques allow a larger system of equations to be handled without execution time penalty for using the complete matrices.

CHAPTER III

METHODOLOGY

Physical Background

Infiltration and ventilative airflows occur due to the pressure difference caused by wind, density difference (stack effect), and mechanical ventilation systems. The pressure difference between any two nodes depends on magnitude of one or all these factors as well as the physical characteristics of building airflow openings.

Bernoulli's equation, which governs flow within each airflow element, is the fundamental equation necessary to understand and predict behavior of airflow in a building exposed to combined influence of outdoor climate (wind, outdoor temperature, pressure, and humidity) and indoor climate (temperature, mechanical ventilation systems, and humidity).

$$\Delta P = \left[P_i + \frac{\rho V_i^2}{2} + \rho g z_i \right] - \left[P_j + \frac{\rho V_j^2}{2} + \rho g z_j \right] \quad [3.1]$$

ΔP = total pressure drop between the ends of a link connecting nodes i and j (Pa)

P_i, P_j = entry and exit static pressures (Pa)

ρ = air density (kg/m³)

V_i, V_j = entry and exit velocity of air through the link (m/s)

g = gravitational constant (9.8 m/s²)

z_i, z_j = entry and exit elevation of the link (m)

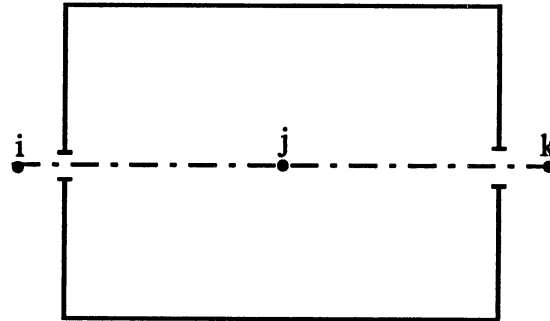


Figure 3.1 Schematic Representation of a Simple 3-Node Network

The total pressure difference between the nodes i and j can be expressed as follows:

$$\Delta P = P_i - P_j + \Delta P_{\text{wind}} + \Delta P_{\text{stack}} \quad [3.2]$$

P_i, P_j = static pressure of nodes i and j at their reference heights in an undisturbed flow without wind and stack effects (Pa)

ΔP_{wind} = pressure difference between nodes i and j due to wind (Pa)

ΔP_{stack} = pressure difference between nodes i and j due to difference in density (Pa)

When ventilation fans are in operation, an additional airflow is imposed. The above expression for pressure difference is still valid, but node pressures change correspondingly so that balance between incoming flow and outgoing flow is maintained.

Wind Pressure

An instantaneous over-pressure is created when flow hits an obstacle. Generally, on the windward side of a building the wind pressure is positive and it is negative on leeward side. Pressure on the other sides are either positive or negative depending on wind incidence angle and building configuration.

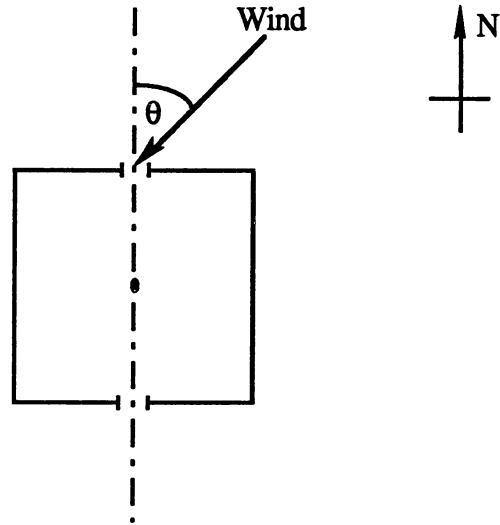


Figure 3.2 Wind Pressure Acting on a Building Surface

The dynamic pressure on a surface k due to wind with incidence angle θ° (wind angle measured from north direction) is given by the Bernoulli's equation as follows:

$$P_{k\theta} = C_{p_{k\theta}} \frac{\rho V^2}{2} \quad [3.3]$$

$P_{k\theta}$ = wind pressure acting on the surface k due to wind with an incident angle θ° (Pa)

$C_{p_{k\theta}}$ = empirical surface pressure coefficient for surface k for wind angle θ°

ρ = air density (kg/m^3)

V = free stream wind velocity (m/s)

Wind pressure at a point on a building surface at any height can be calculated as follows:

$$P = P_{k\theta} + \rho g (h_r - h) \quad [3.4]$$

where h_r is reference height of wind at which wind pressure $P_{k\theta}$ is computed and h is height of the point.

Stack Pressure

Temperature difference between two interconnected nodes in a building causes density difference and hence pressure difference which drives airflow between those two nodes. The height at which the node pressures are equal is called the neutral pressure level.

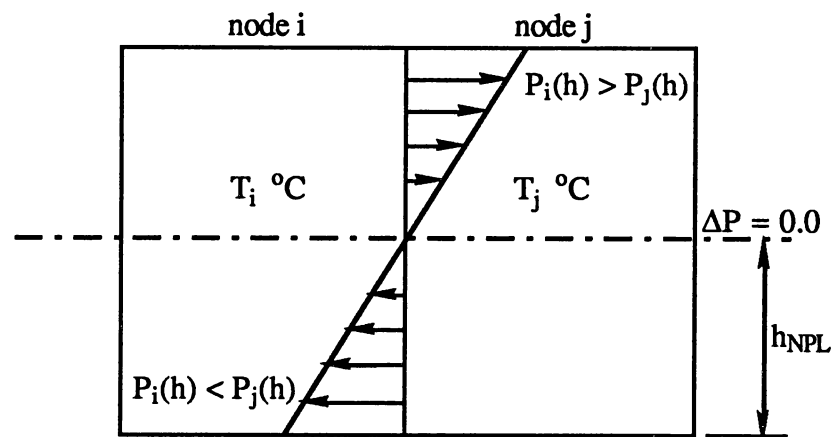


Figure 3.3 Buoyancy Driven Airflow

By hydrostatic law, the pressure difference due to the stack effect at any height h can be given as follows:

$$\Delta P_{\text{stack}} = \rho_i g (h - h_{\text{NPL}}) - \rho_j g (h - h_{\text{NPL}}) \quad [3.5]$$

ρ_i, ρ_j = air densities of nodes i and j (kg/m^3)

g = gravitational constant (9.8 m/s^2)

h_{NPL} = height of neutral pressure level (m)

Actually the calculation of stack pressures should go side by side with iterative solution process because the nodal densities change corresponding to nodal pressures. Hence stack pressures need to be updated in each iteration. However this process often interferes with the fast convergence of solution. In order to overcome this problem in the Network model, the stack pressures are left unchanged during the iterative solution process till the solution converges. Once the solution is converged, the stack pressures are updated making use of most recent values of node pressures. The iterative solution process is further carried out until the solution converges in the first iteration itself after updating the stack pressures. This technique gives comparatively faster solutions.

Internal partitions, shafts, staircases, chimneys, mechanical supply and exhaust systems make stack pressure calculations quite complex. Detailed discussion of buoyancy driven airflow can be found in Brown and Solvason (1962), Hill et al. (1986) and Barakat (1987).

Description of Flow Formulation

In the following paragraphs modeling of the main types of building airflow elements such as cracks and doorways, and duct airflow elements such as ducts and fans are discussed. Emphasis is on discussion of formulation of flow and flow derivatives, and examining governing physical laws and correlations. Many of the concepts and algorithms used in these models and airflow network solution method are based on the Airnet model of Walton (1989).

The nodal air density and dynamic viscosity required for flow calculations are calculated as follows:

From the ideal gas law, the density of air at i th node:

$$\rho_i = \frac{\text{Bar Pressure} + P_i}{R * (273.15 + T_i)} \quad (\text{kg/m}^3) \quad [3.6]$$

The dynamic viscosity of air at i th node is computed as follows (Walton, 1989):

$$\mu_i = 1.71432 \times 10^{-5} + 4.828 \times 10^{-8} T_i \text{ (kg/m-s)} \quad [3.7]$$

T_i = node temperature ($^{\circ}\text{C}$)

P_i = node pressure (Pa)

R = gas constant for air (287 J/kg-K)

Crack Airflow Modeling

Generally the flow of air through cracks is approximated by a powerlaw equation of the form indicated below. This equation is a correlation rather than a physical law.

$$\dot{m} = C \sqrt{\rho_i} (\Delta P)^x \quad \text{when } \Delta P > 0 \quad [3.8a]$$

$$\dot{m} = - C \sqrt{\rho_j} (-\Delta P)^x \quad \text{when } \Delta P < 0 \quad [3.8b]$$

\dot{m} = mass flow rate of air through the crack from node i to node j (kg/s)

C = flow coefficient

ρ_i, ρ_j = air densities of nodes i and j (kg/m^3)

$\Delta P = P_i - P_j$ (Pa)

P_i, P_j = pressure of nodes i and j at the ends of crack (Pa)

x = powerlaw flow exponent

The above equation is a correlation rather than a physical law. Flow coefficient C is related to area of opening and its discharge coefficient as follows (ASHRAE, 1989, Page 23.6):

$$C = C_D A \sqrt{2} \quad [3.9]$$

where A is opening area in m^2 , and the discharge coefficient C_D is a dimensionless number that depends on the opening geometry and the Reynolds number of the flow. For laminar

flows it depends on the square root of the pressure difference and at sufficiently high Reynolds numbers (i.e., for turbulent flows) it is constant.

Flow exponent x characterizes the flow regime and has values between 0.5 and 1.0. Large openings at high Reynolds number (i.e., turbulent flows) are characterized by values near 0.5, while cracks with large aspect ratio (i.e., with greater depths or narrower widths) tend to have values closer to 1.0. This value practically rises to unity for completely laminar flows.

The partial derivatives of the equations [3.8a and 3.8b] which are used in Newton's method to solve the simultaneous flow equations are computed analytically as follows:

$$\frac{\partial \dot{m}}{\partial P_i} = x \left(C \sqrt{\rho_i} (P_i - P_j)^{x-1} \right) \quad [3.10]$$

$$= x C \sqrt{\rho_i} \frac{\Delta P^x}{\Delta P} \quad [3.11]$$

Hence

$$\frac{\partial \dot{m}}{\partial P_i} = \frac{x \dot{m}}{\Delta P} \quad [3.12a]$$

Similarly

$$\frac{\partial \dot{m}}{\partial P_j} = - \frac{x \dot{m}}{\Delta P} \quad [3.12b]$$

The basic advantage of the form used in equations [3.12a and 3.12b] is the simple calculation of partial derivatives used in Newton's method.

But these derivatives become unbounded as pressure drop and subsequently airflows go to zero. However at low flow rates the flow changes from turbulent to laminar.

Laminar flow is given by the following equation (Walton, 1989):

$$\dot{m} = \frac{k \rho \Delta P}{\mu} \quad [3.13]$$

k = laminar flow coefficient

ρ = air density (kg/m^3)

μ = dynamic viscosity (kg/m-s)

The laminar flow coefficient k is given by:

$$k = \frac{2 A D_h C_D^2}{\text{Re}} \quad [3.14]$$

C_D = discharge coefficient

A = opening area (m^2)

D_h = hydraulic diameter of the opening (m)

Re = Reynolds number for flow transition (in the present context its value is about 100)

The partial derivatives of the laminar flow equation are simple constants and they are computed as follows:

$$\frac{\partial \dot{m}}{\partial P_i} = \frac{k \rho}{\mu} \quad [3.15a]$$

$$\frac{\partial \dot{m}}{\partial P_j} = - \frac{k \rho}{\mu} \quad [3.15b]$$

As at low flow rates the flow changes from turbulent to laminar, the subroutine for calculation of airflow through cracks computes both turbulent and laminar flows, then chooses the method giving smaller magnitude of flow. There is a discontinuity in the derivative of the Flow-Pressure Drop curve where the laminar and turbulent flow equations intersect and this is a violation of one of the conditions for convergence in Newton's method. But the numerical tests conducted by Walton (1989) using a small airflow network

for calculating the flows in the region of discontinuity have shown no convergence problem.

Real buildings often have multiple cracks which would make the airflow networks very complicated. The concept of effective airflow elements (Walton, 1989) can be used for simplifying such networks as follows:

a) In the case of series flow paths :

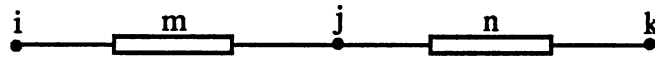


Figure 3.4 Crack Airflow Elements in Series

Pressure drop between nodes i and k,

$$P_i - P_k = (P_i - P_j) + (P_j - P_k) \quad [3.16]$$

Flow through links m and n:

$$\dot{m} = \dot{m}_n = \dot{m}_m \quad [3.17]$$

i) For laminar flow through links m and n:

$$P_i - P_k = \dot{m} \left(\frac{\mu}{\rho} \right) \left(\frac{1}{k_m} + \frac{1}{k_n} \right) \quad [3.18]$$

$$\dot{m} = \left(\frac{\rho}{\mu} \right) k_e (P_i - P_k) \quad \text{where } \frac{1}{k_e} = \left(\frac{1}{k_m} + \frac{1}{k_n} \right) \quad [3.19]$$

So for laminar flow for elements in series:

$$k_e = \frac{1}{\sum \frac{1}{k_{LINK}}} \quad [3.20]$$

ii) For turbulent flow through links m and n:

$$P_i - P_k = \dot{m}^2 \left(\frac{1}{\rho} \right) \left(\frac{1}{C_m^2} + \frac{1}{C_n^2} \right) \quad [3.21]$$

$$\dot{m} = \sqrt{\rho} C_e \sqrt{P_i - P_k} \quad \text{where} \quad \frac{1}{C_e^2} = \left(\frac{1}{C_m^2} + \frac{1}{C_n^2} \right) \quad [3.22]$$

So for turbulent flow for elements in series :

$$C_e = \frac{1}{\sqrt{\sum \frac{1}{C_{LINK}^2}}} \quad [3.23]$$

a) In case of parallel flow paths :

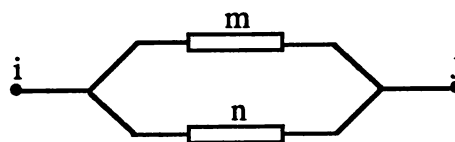


Figure 3.5 Crack Airflow Elements in Parallel

$$\text{Total flow } \dot{m} = \dot{m}_n + \dot{m}_m \quad [3.24]$$

i) For laminar flow through links m and n:

$$\dot{m} = \left(\frac{\rho}{\mu} \right) (k_m + k_n) (P_i - P_j) \quad [3.25]$$

So for laminar flow for elements in parallel:

$$k_e = \Sigma k_{\text{LINK}} \quad [3.26]$$

ii) For turbulent flow through links m and n:

$$\dot{m} = \sqrt{\rho} (C_m + C_n) \sqrt{P_i - P_j} \quad [3.27]$$

So for turbulent flow for elements in parallel:

$$C_e = \Sigma C_{\text{LINK}} \quad [3.28]$$

Doorway Airflow Modeling

Analysis of airflow through large openings like doorways is more complicated than flow through small crack like openings because of the possibilities of two-way flow. Nodal temperature difference and thereby density difference lead to stack effect causing positive pressure difference at the top and negative pressure difference at the bottom of a doorway, or vice versa depending on nodal densities.

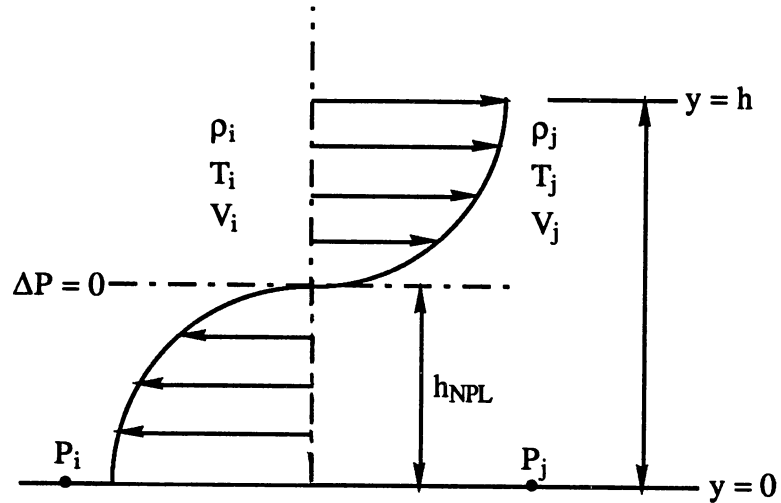


Figure 3.6 Schematic Representation of Airflow across Doorway Element

In the above Figure:

P_i, P_j = node pressures (Pa)

ρ_i, ρ_j = node air densities (kg/m^3)

V_i, V_j = node air velocities (m/s)

T_i, T_j = node temperatures ($^{\circ}\text{C}$)

h = door height (m)

h_{NPL} = height of neutral pressure level (m)

Assuming no changes in air density with height in the rooms, by hydrostatic law static pressure $P(y)$ at any height y (measured with respect to node height) can be given by:

$$P(y) = P_{\text{REF}} - \rho g y \quad [3.29]$$

where P_{REF} is the static pressure at node height level (i.e., P_i or P_j).

Air velocity (V m/s) as a function of opening height can be given by orifice equation as follows:

$$V(y) = C_D \sqrt{\frac{2 (P_i(y) - P_j(y))}{\rho}} \quad [3.30]$$

where C_D is discharge coefficient of the door.

Neutral plane height h_{NPL} at which air velocity is zero and also pressure difference between two nodes is zero, is given by:

$$h_{NPL} = \frac{P_i - P_j}{g (\rho_i - \rho_j)} \quad [3.31]$$

Two-way airflow exists if the following conditions are satisfied: i) node densities are not equal (if the densities are equal the opening between the two nodes can be handled as a simple powerlaw element). ii) h_{NPL} is not smaller than zero or greater than the door height.

On transforming the height coordinates i.e., taking $z = (h_{NPL} - y)$, the two-way airflow across the doorway for different cases can be given as follows:

Case 1. Mass flow rate above the neutral height

$$\text{For flow from node i to j, } \dot{m}_{top} = \int_{z=0}^{z=h-h_{NPL}} \rho_i V_i w dz \quad [3.32a]$$

$$\text{For flow from node j to i, } \dot{m}_{top} = \int_{z=0}^{z=h-h_{NPL}} \rho_j V_j w dz \quad [3.32b]$$

Case 2. Mass flow rate below the neutral height

$$\text{For flow from node i to j, } \dot{m}_{bottom} = \int_{z=-h_{NPL}}^{z=0} \rho_i V_i w dz \quad [3.32c]$$

$$\text{For flow from node } j \text{ to } i, \dot{m}_{\text{bottom}} = \int_{z = -h_{\text{NPL}}}^{z = 0} \rho_j V_j w \, dz \quad [3.32d]$$

where w is the width of doorway (m).

Upon the integration of the above equations, different solutions for airflows are obtained depending on neutral plane height and nodal density differences. Walton (1989) has defined few flow factors as follows which will allow convenient expressions for the flow and flow derivatives:

$$A = \frac{2}{3} w C_D \sqrt{2g|\rho_i - \rho_j|} \quad [3.33a]$$

$$A' = w C_D \sqrt{\frac{2}{g|\rho_i - \rho_j|}} \quad [3.33b]$$

$$W_{\text{top}} = \sqrt{|h - h_{\text{NPL}}|^3} \quad [3.33c]$$

$$W_{\text{bottom}} = \sqrt{|h_{\text{NPL}}|^3} \quad [3.33d]$$

$$W'_{\text{top}} = \sqrt{|h - h_{\text{NPL}}|} \quad [3.33e]$$

$$W'_{\text{bottom}} = \sqrt{|h_{\text{NPL}}|} \quad [3.33f]$$

i) If $h_{\text{NPL}} \leq 0$ then:

Case 1. When $\rho_i - \rho_j > 0$

$$\dot{m} = -A \sqrt{\rho_j} |W_{\text{top}} - W_{\text{bottom}}| \quad [3.34a]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_j} |W'_{\text{top}} - W'_{\text{bottom}}| \quad [3.34b]$$

Case 2. When $\rho_i - \rho_j < 0$

$$\dot{m} = A \sqrt{\rho_i} |W_{\text{top}} - W_{\text{bottom}}| \quad [3.34c]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_i} |W'_{\text{top}} - W'_{\text{bottom}}| \quad [3.34d]$$

ii) If $h_{\text{NPL}} \geq h$ then:

Case 1. When $\rho_i - \rho_j > 0$

$$\dot{m} = A \sqrt{\rho_i} |W_{\text{top}} - W_{\text{bottom}}| \quad [3.35a]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_i} |W'_{\text{top}} - W'_{\text{bottom}}| \quad [3.35b]$$

Case 2. When $\rho_i - \rho_j < 0$

$$\dot{m} = -A \sqrt{\rho_j} |W_{\text{top}} - W_{\text{bottom}}| \quad [3.35c]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_j} |W'_{\text{top}} - W'_{\text{bottom}}| \quad [3.35d]$$

iii) If $0 < h_{\text{NPL}} < h$ then:

Case 1. When $\rho_i - \rho_j > 0$

$$\dot{m}_{\text{top}} = -A \sqrt{\rho_j} W_{\text{top}} \quad [3.36a]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_j} W'_{\text{top}} \quad [3.36b]$$

$$\dot{m}_{\text{bottom}} = A \sqrt{\rho_i} W_{\text{bottom}} \quad [3.36c]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_i} W'_{\text{bottom}} \quad [3.36d]$$

Case 2. When $\rho_i - \rho_j < 0$

$$\dot{m}_{\text{top}} = A \sqrt{\rho_i} W_{\text{top}} \quad [3.36e]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_i} W'_{\text{top}} \quad [3.36f]$$

$$\dot{m}_{\text{bottom}} = -A \sqrt{\rho_j} W_{\text{bottom}} \quad [3.36g]$$

$$\frac{\partial \dot{m}}{\partial P_i} = A' \sqrt{\rho_j} W'_{\text{bottom}} \quad [3.36h]$$

And for all these above cases:

$$\frac{\partial \dot{m}}{\partial P_j} = - \frac{\partial \dot{m}}{\partial P_i} \quad [3.37]$$

Occurrence of two-way airflow necessitates keeping track of flow directions through the solution process and while transferring the building airflows to calling BLAST subroutine. However, the algorithm discussed above for modeling doorway airflow is much faster than an equivalent multiple opening approach.

Duct Airflow Modeling

The two types of duct pressure losses include frictional losses and dynamic losses. Frictional losses occur along the entire duct length. Dynamic losses result from flow disturbances caused by duct fittings that change either the direction of flow path, or area, or both. These fittings include entries, exits, transitions and junctions.

Frictional losses for airflow in ducts can be calculated by using the Darcy-Weisbach equation:

$$\Delta P_f = \frac{\rho f L V^2}{2 D_h} \quad [3.38]$$

f = friction factor

L = duct length (m)

D_h = hydraulic diameter of duct (m)

ρ = air density (kg/m³)

V = air velocity (m/s)

For turbulent flows, friction factor f depends on Reynolds number, duct surface roughness and internal joints. It can be computed using the nonlinear Colebrook's equation (ASHRAE, 1989, Page 32.4)

An alternative to Colebrook's equation, a simplified explicit formula known as Altshul's modified equation (ASHRAE, 1989, Page 32.5) can be used:

$$f' = 0.11 \left(\frac{\epsilon}{D_h} + \frac{68}{Re} \right)^{\frac{1}{4}} \quad [3.39a]$$

$$\text{If } f' \geq 0.018, \text{ then } f = f' \quad [3.39b]$$

$$\text{If } f' < 0.018, \text{ then } f = 0.85 f' + 0.0028 \quad [3.39c]$$

ϵ = material absolute roughness factor (m)

D_h = hydraulic diameter of duct (m)

$$Re = \frac{\rho V D_h}{\mu} = \frac{\dot{m} D_h}{\mu A} \quad [3.40]$$

Dynamic losses due to duct fittings in the case of turbulent flows is given by:

$$\Delta P_d = \frac{C \rho V^2}{2} \quad [3.41]$$

where C is the turbulent dynamic loss coefficient of a duct fitting.

For the cases where duct area remains constant and flow does not split (e.g., for bends, elbows etc., but not for transitions and junctions) the total pressure loss is the sum of frictional and dynamic losses. However when there is split in duct airflow or change in duct area at the duct fittings only dynamic losses are accounted.

$$\Delta P = \Delta P_f + \Sigma \Delta P_d \quad [3.42]$$

$$\Delta P = \frac{\rho f L V^2}{2 D_h} + \frac{\rho V^2}{2} \Sigma C \quad [3.43]$$

Putting $\dot{m} = \rho VA$ in the above equation and rearranging the equation

$$\dot{m} = \sqrt{\frac{2 \rho A^2}{f L/D_h + \Sigma C} \Delta P} \quad [3.44]$$

The partial derivatives of the above duct airflow equation can be conveniently expressed in a simple form as follows:

$$\frac{\partial \dot{m}}{\partial P_i} = \frac{1}{2} \frac{\dot{m}}{\Delta P} \quad [3.45a]$$

$$\frac{\partial \dot{m}}{\partial P_j} = -\frac{1}{2} \frac{\dot{m}}{\Delta P} \quad [3.45b]$$

These above algorithms apply to flows in only turbulent regime. When the flow regime is below critical Reynolds number ($Re_{crit} \approx 2000$), the flow is laminar, and the friction factor f in the Darcy-Weisbach equation is inversely proportional to Reynolds number for these flows.

$$f = \frac{k}{Re} \quad [3.46]$$

where the dimensionless factor laminar frictional loss coefficient k is dependent only on the shape of duct cross section and is largely independent of duct surface roughness. Values of k for various duct cross sections can be found in the Applied Fluid Dynamics Handbook (Blevins, 1984, Chapter 6).

Hence the laminar frictional loss is given by:

$$\Delta P_f = \frac{\rho k L V^2}{2 Re D_h} \quad [3.47]$$

Substituting for Reynolds number [Equation 3.40] in the above equation, laminar frictional loss:

$$\Delta P_f = \frac{\mu k L \dot{m}}{2 \rho A D_h^2} \quad [3.48]$$

where μ is dynamic viscosity (kg/m-s).

Laminar dynamic losses can be computed as follows:

$$\Delta P_d = \frac{K \rho V^2}{2} = \frac{K \dot{m}^2}{2 \rho A^2} \quad [3.49]$$

where K is laminar dynamic loss coefficient of a duct fitting.

Hence for the cases where duct area remains constant and flow does not split, the total pressure loss:

$$\Delta P = \Delta P_f + \Sigma \Delta P_d \quad [3.50]$$

Upon substitution, this gives a quadratic equation of the form:

$$a \dot{m}^2 + b \dot{m} + c = 0 \quad [3.51]$$

where $a = \frac{K}{2 \rho A^2}$, $b = \frac{\mu k L}{2 \rho A D_h^2}$ and $c = |\Delta P|$

$$\text{Hence } \dot{m} = \frac{(-b + \sqrt{b^2 + 4ac})}{2a} \quad \text{when } \Delta P > 0 \quad [3.52a]$$

$$\dot{m} = \frac{(b - \sqrt{b^2 + 4ac})}{2a} \quad \text{when } \Delta P < 0 \quad [3.52b]$$

The partial derivatives for laminar flow can be calculated as follows:

$$\frac{\partial \dot{m}}{\partial P_i} = \frac{1}{\sqrt{b^2 + 4ac}} \quad [3.53a]$$

$$\frac{\partial \dot{m}}{\partial P_j} = \frac{-1}{\sqrt{b^2 + 4ac}} \quad [3.53b]$$

Hence the derivatives do not go unbounded even when ΔP is very small, and also the derivatives are finite at $\Delta P = 0$

Fan Airflow Modeling

Energy transferred by a fan impeller results in an increase in static and velocity heads of air-stream flowing across it. Assuming constant density and constant power delivery by the fan, airflow across the fan is given by:

$$\dot{m} = \frac{\rho W}{\Delta P} \quad [3.54]$$

ρ = air density (kg/m³)

W = fan power (W)

ΔP = total pressure rise across the fan (Pa)

The partial derivatives of the above fan airflow equation can be computed analytically as follows:

$$\frac{\partial \dot{m}}{\partial P_i} = \frac{\dot{m}}{\Delta P} \quad [3.55a]$$

$$\frac{\partial \dot{m}}{\partial P_i} = - \frac{\dot{m}}{\Delta P} \quad [3.55b]$$

In some cases this formulation can lead to physically untenable solutions (e.g., negative pressure rise, negative mass flow rate). This problem is overcome in the Network fan model by setting the pressure rise to be positive if it should somehow become negative in the iterative solution process. This prevents convergence to wrong solution.

Solution Method

Basic equations governing flows in an airflow network are those of continuity expressed at each node as:

$$\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out} \quad [3.56]$$

Airflow networks have both known and unknown pressure nodes. At least one of the node pressures should be known to compute other unknown pressures and flow rates in the network. All nodes must be connected to a known pressure node through some path. Generally, for each hour ambient nodes are assigned pressure and temperature values from known surface pressure coefficients and weather data. On applying the law of conservation of mass at each node, a set of simultaneous nonlinear governing equations are obtained

which are to be solved iteratively. It is important that the method be robust and converge rapidly to the correct solution. Newton's method is used for solving these equations in the Network model.

The principle on which Newton's method works can be illustrated briefly as follows (Kincaid and Cheney, 1991):

Consider r to be the zero of function f and let x be an approximation to r . If f' exists and is continuous, then by Taylor's theorem:

$$f(r) = f(x+h) = f(x) + h f'(x) + O(h^2) = 0 \quad [3.57]$$

where $h = r - x$ and $O(h^2)$ is a sequence consisting of remaining terms in the Taylor's series. If h is small (i.e., x is near to r), then it is reasonable to ignore the $O(h^2)$ term and on solving the remaining equation for h ,

$$h = \frac{-f(x)}{f'(x)} \quad [3.58]$$

So if x is an approximation to r , then

$$x - \frac{f(x)}{f'(x)} \quad [3.59]$$

should be a better approximation to r . Newton's method begins with an initial estimate x_0 of r and then defines inductively:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (n \geq 0) \quad [3.60]$$

In the case of airflow networks, new estimates of all node pressures $[P_{n+1}]$ can be computed from current estimates of pressures $[P_n]$ by applying a correction vector C which is computed by matrix relationship:

$$[J] [C] = [F] \quad [3.61]$$

where $[F]$ is a column vector for residual flows (i.e., obtained by applying conservation of mass equation at each node) whose i th row elements are given by:

$$F_i = \sum_{n=1}^{n=ncl} \dot{m}_{(i, n)} \quad [3.62]$$

$\dot{m}_{(i, n)}$ = airflow across the link n connecting node i to another node

ncl = total number of links connected to node i .

$[J]$ is a Jacobian matrix of the order $N \times N$ for an airflow network of N unknown pressure nodes. The elements of a Jacobian matrix are obtained by taking partial derivatives of mass conservation equations shown above with respect to current estimates of node pressures.

Symbolically, a Jacobian matrix can be represented as follows:

$$J_{(i, j)} = \sum_{n=1}^{n=ncl} \frac{\partial \dot{m}_{(i, n)}}{\partial P_j} = \begin{bmatrix} \frac{\partial F_1}{\partial P_1} & \frac{\partial F_1}{\partial P_2} & \dots \\ \frac{\partial F_2}{\partial P_1} & \frac{\partial F_2}{\partial P_2} & \dots \\ \dots & \dots & \dots \end{bmatrix} \quad [3.63]$$

$\frac{\partial F_i}{\partial P_j}$ = partial derivative of the conservation of mass equation at node i
with respect to the j th node pressure.

First, initial guesses are assigned to each unknown pressure node. Then equation [3.61] is iteratively applied to achieve mass balance at each unknown pressure node and hence establish the nodal pressures. Equation [3.61] is a set of linear equations that can be

solved using any linear equation solving routines like Standard Gaussian Elimination or Lower Upper Decomposition, or by using the sparse matrix solution techniques. The Network model uses Lower Upper Decomposition routines for this purpose.

Initialization of Node Pressures

The initial guess of nodal pressures is important. With poor starting points, Newton's method may not converge at all. These starting pressures can be estimated assuming a linear relationship between flow and pressure drop.

$$m = a + b \Delta P \quad [3.64]$$

where a and b are simple constants.

This linear approximation to flow can be obtained from flow in laminar flow domain. Initialization for each hour may not be required, especially when wind pressure and wind direction are changed by small amounts. The previous solutions for the node pressures can be then used as starting values. However in order to accommodate the worst possible hourly variations in wind speed and wind direction, the Network model does the initialization for each hour.

Here again the conservation of mass at each node is the source of governing equations represented as follows:

$$[A] [P] = [F] \quad [3.65]$$

[A] = coefficient matrix

[P] = matrix of node pressures

[F] = residual flow matrix

The same linear equation solver routine used in the process of solving the nonlinear flow equations can be used for solving the above for starting values of node pressures. In

the case of a doorway element, initialization is done assuming doorway airflow as one-way flow, and crack flow initialization routine is used for this purpose.

Numerous numerical tests conducted by the author using a variety of airflow networks have confirmed that this linear flow relationship gives good starting points which allow faster convergence of solution.

Convergence Criteria for Network Solution

Conservation of mass at each node provides the convergence criterion. If $\sum \dot{m} \leq \epsilon_A$ (ϵ_A is absolute convergence criterion) at all nodes based on current estimates of node pressures, the solution has converged. Furthermore, many iterations can be saved by testing for relative convergence at each node with some suitable relative convergence allowance ϵ_R such that:

$$\frac{|\sum \dot{m}|}{\sum |\dot{m}|} \leq \epsilon_R \quad [3.66]$$

The magnitude of these absolute and relative convergence criteria can be chosen based on accuracy and need of modeling.

Especially in the near neighborhood of the solutions, Newton's method is more rapidly convergent compared to any other solution method for nonlinear equations. When it converges, Newton's method usually converges quadratically which means that error at each new step approaches a constant times the square of error at the previous step. However, there are instances of very slow convergence of Newton's method with oscillating corrections in successive steps of iteration process. This problem can be avoided by applying a constant under-relaxation factor on the newly obtained values of corrections. Another technique is to use Steffensen iteration (Conte and de Boor, 1972) to extrapolate the correction to an assumed solution as follows :

$$P_{n+1} = P_n - \frac{C_{NEW}}{(1 - r)} \quad \text{where } r = \frac{C_{NEW}}{C_{OLD}} \quad [3.67]$$

C_{NEW} = correction for the current iteration (Pa)

C_{OLD} = correction for the previous iteration (Pa)

P_n, P_{n+1} = current and new estimates of node pressure (Pa)

When $r < 0$, this will lead to smaller corrections as compared to a simple Newton's iteration. Though it has not been proved that use of Steffensen iteration will always lead to convergence, it can be shown that there is no reason for it to prevent convergence. As in this method there is an emphasis on the trend of correction values in the iterative solution process, it seems to be comparatively a better technique than using simple Newton's iterations or constant under-relaxation method. A variety of numerical tests conducted by the author have confirmed that this technique leads to faster convergence than using constant under-relaxation factor. The results of these tests are discussed in Chapter IV. The application of the above equation is limited for situations where r is less than -0.5 (Walton, 1989), and it is observed that this will not interfere with rapid convergence of solution.

Structure of the Stand-Alone Version of the Network Model

The source code of the Network model is written in FORTRAN 77. It contains nineteen subroutines. Because of the need of accuracy in numerical computations, the double precision data type is used throughout the program. The entire structure of the program is devised in a very flexible way such that any future addition and development in the model should require minimal modifications in the basic structure of the program.

As the program is written with an intention of implementing it into BLAST program, it is not user interactive. All necessary input data has to be stored in ASCII data files. The following three input data files: network data file ("izafnw.dat"), surface pressure coefficient data file ("izafcp.dat"), and weather data file ("izafweth.dat") are required during

execution of the program. The program needs two "INCLUDE" files, one for specifying the array dimensions to suit the size of network and for specifying the number of pressure coefficient values available for each exterior building surface ("size.inc"), and another for holding the common blocks which store the input and output data ("izaf.inc").

Figure 3.7 provides the flowchart showing a simplified structure of the stand-alone version of the Network program. Sample network, surface pressure coefficient and weather data files can be found in Appendix A.

The network data input file is to be prepared by the user which contains information about nodes, linkage and flow characteristics of connecting links. Making use of available surface pressure coefficient database, the user can prepare a pressure coefficient data file for exterior surfaces of the building (ambient nodes). The program has routines to calculate ambient node pressures using the wind and surface pressure coefficient data, and stack pressures based on nodal air density differences.

The main body of the program consists of two major parts. One part (subroutine "read_network_dat") reads network and surface pressure coefficient data, and it does mapping of the data based on element, linkage, and node information. Then the data is stored in the proper arrays specified in the common blocks. The second part (subroutine "calc_interzone_airflow") reads weather data file and computes building surface pressures. Then it carries out the initialization of node pressures, solves airflow network and prints a formatted output.

As the algorithms for the solution of nonlinear flow equations are based on Newton's method, proper initialization of unknown node pressures is very important. In the Network program, the starting values of these unknown node pressures are computed by assuming linear flow relationship between flow and pressure drop. The program is provided with routines for computing the linear flows and flow derivatives separately for crack/door, duct and fan elements.

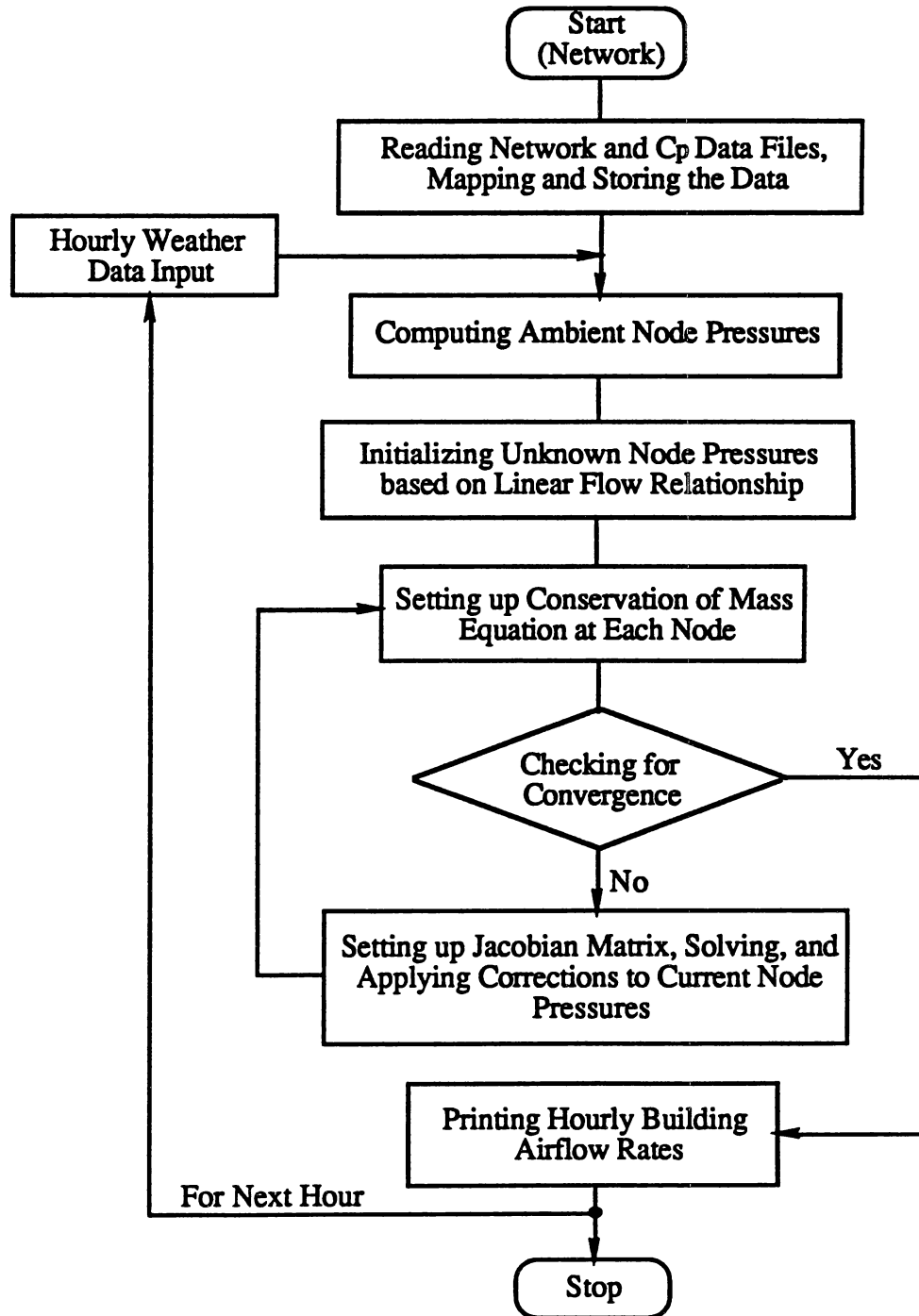


Figure 3.7 Flowchart for the Stand-Alone Version of the Network Model

Once these initial values of node pressures are made available, residual quantities of conservation of mass flow of air at each variable pressure node and subsequently partial derivatives of these residual quantities with respect to each node pressures are determined. These are stored in a two-dimensional array forming a Jacobian matrix. Gerald and Wheatley (1989) provides routines which produce lower and upper decomposition of a coefficient matrix and solve a system of linear equations. The Network model uses these routines with slight modification in them for solving the Jacobian matrix. The solution process is carried out until it converges satisfying both absolute and relative convergence criteria to user defined epsilon values (i.e., allowances for convergence) by repeatedly applying the corrections to the pressure term of each unknown pressure node. For computing the airflows and flow derivatives in each iteration, separate routines are provided for all the flow elements such as cracks, doors, ducts, and fans.

Also a check for convergence of solution is made every time after updating stack pressure difference between the nodes. The program is provided with intermittent checks to terminate an iterative loop if the solution is getting worse or if the iterative process is going to an infinite loop.

An output file of the Network program contains the data such as initialized and finally computed pressures at each node, airflow rates across each link, and inter-node airflow rates.

Structure of the BLAST-Coupled Version of the Network Model

BLAST is a comprehensive hourly building energy simulation research program which is capable of predicting building loads and energy system performance in buildings. BLAST can also be used in determining the proper equipment type, size and control. The program has its own user-oriented, unformatted, and english-like input language and is accompanied by a library which contains the properties of a variety of materials, walls, roofs, and floor sections.

Zone heat balance is an important aspect in space loads analysis. For each hour simulated, BLAST performs a complete conduction, convection, and radiant heat balance for each building surface and a heat balance on the zone air. BLAST is provided with routines which can completely analyze transient heat conduction through walls and heat storage in zones. The zone heat balance includes transmission loads, solar loads, internal heat gains, infiltration loads, and control strategy used to maintain the space temperature.

The current version of BLAST program does not have the capability to calculate wind driven ventilation and has no features to accurately predict interzone mixing, rather user must schedule interzone mixing. Furthermore infiltration loads are determined based on user specified infiltration and ventilation airflow rates. The implementation of the Network model has enabled BLAST to accurately predict the infiltration loads based on actual building airflows rather than requiring users to specify the building infiltration and ventilation flow rates.

Except for very few alterations, the major portion of the structure of the BLAST-coupled version of the Network model is similar to the stand-alone version of the Network model. Figure 3.8 provides the flowchart showing a simplified structure of the BLAST program coupled with the Network model. The portion enclosed within the dotted lines of the flowchart is the part of the Network model implemented into BLAST .

Unlike the stand-alone version, the BLAST coupled version does not require "izafweth.dat" weather data input file. The other necessary input data files such as "izafnw.dat" and "izafcp.dat" are associated with unit numbers 93 and 94. The program needs eight "INCLUDE" files consisting of "size.inc" file and seven other files (izaf1.inc, izaf2.inc, - - - - izaf7.inc., for holding the necessary common blocks to store the data).

The Network model routine which reads, maps and stores the input data (i.e., subroutine "read_network_dat") is called by the BLAST routine "SIMBLD" (Simulate Building Loads, grouped under "rout33.ftn"). Later the "VARTMP" routine of BLAST (grouped under "rout34.ftn") calls the Network subroutine "calc_interzone_airflow" which

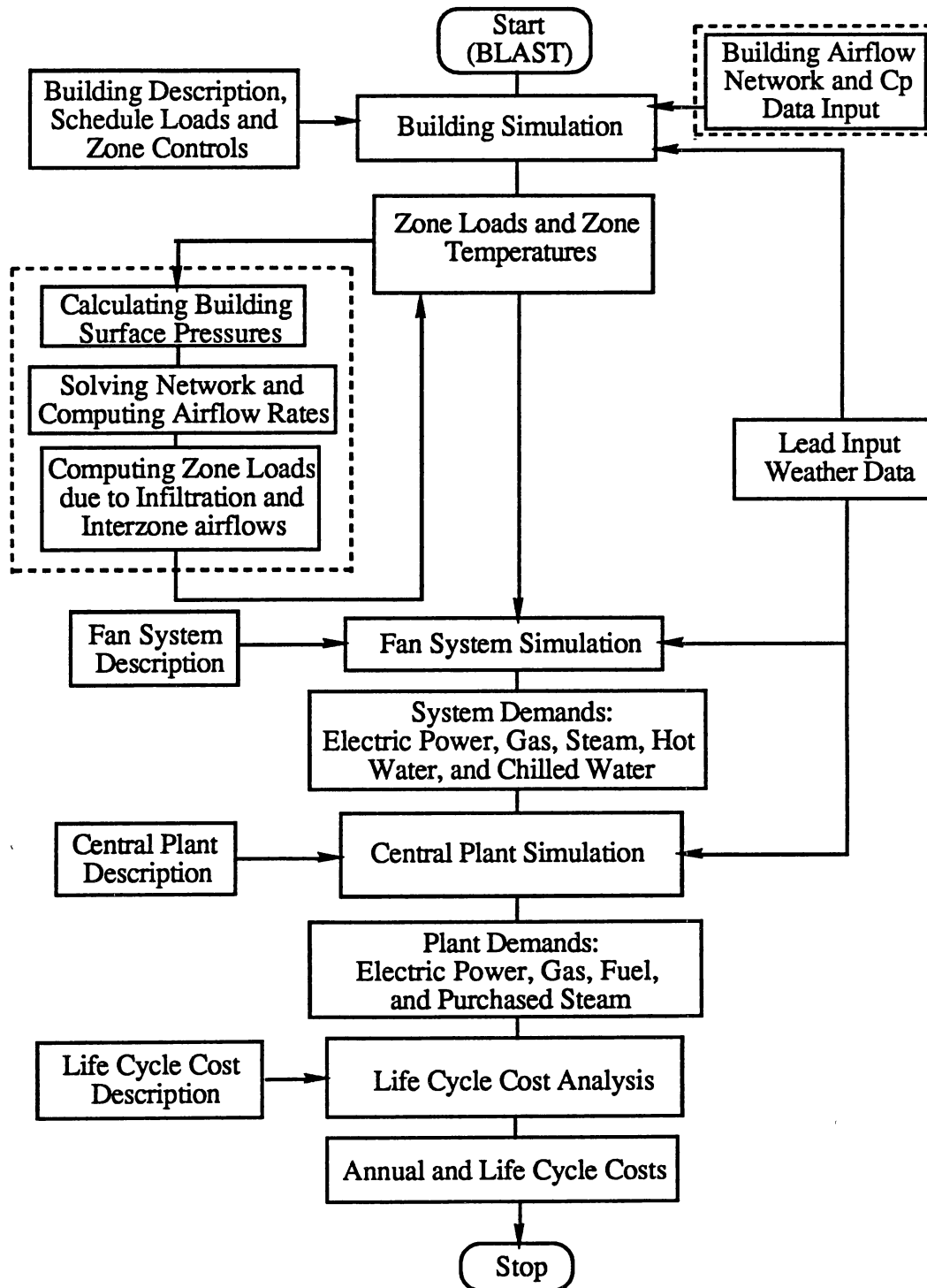


Figure 3.8 Flowchart for the BLAST-Coupled Version of the Network Model

solves building airflow network and computes the building infiltration and interzone airflow rates and stores them in proper common blocks. While calling this subroutine, "VARTMP" passes to it the following data: wind speed, wind direction, barometric pressure, outdoor dry bulb temperature, and mean air temperatures of zones.

The BLAST routines "VARTMP" computes the loads due to infiltration airflows and "HBAIR1" (grouped under "rout26.ftn") computes the loads due to interzone air mixing. Extensive modifications in these routines were made in order to implement the Network model into BLAST. The other modifications carried out in the BLAST program for thermal comfort studies are discussed in Chapter IV.

For the other details of the BLAST program, and its libraries and input files, the BLAST Support Office, Urbana, Illinois or BLAST user's manual may be consulted.

CHAPTER IV

RESULTS AND DISCUSSION

A variety of tests were conducted to ensure the correct implementation of the element airflow models, study computation time requirements, and examine the potential uses of the Network model in modeling attic ventilation and studying zone thermal comfort. Although a large number of tests were conducted during the course of development of the model, only selected tests and their results are presented here.

These tests were conducted on an Apollo workstation. The Apollo workstation was used for several reasons. It provides an excellent environment for FORTRAN program development, especially in development and modification of very large programs like BLAST. Ongoing BLAST development activities at the University of Illinois at Urbana-Champaign use Apollo workstations. Compatibility at this level will help in reducing efforts in porting code from one environment to another.

The network data files used for validation tests of flow elements are provided in Appendix B, and Appendix C contains the sketches of the airflow networks used in computation time tests.

The attic ventilation and thermal comfort tests were conducted on a ranch style house having 111.6 sq.m area (roughly 12.2 x 9.15m). The model of the test house was based on the Karns test houses used by Oak Ridge National Laboratory (Levins and Karnitz, 1987). The location of the test house was assumed to be Columbia, Missouri. The validation tests which were conducted to ensure the correct implementation of the Network model into the BLAST program also used the same test house and location. A sample BLAST input file and the details of the test house are provided in Appendix D. BLAST

requires hourly weather input (environmental parameters such as wind speed, wind direction, dry bulb and wet bulb temperatures, etc.) during execution. A TRY (Test Reference Year) weather tape for Columbia, Missouri was used for this purpose.

Validation Tests

To ensure the correct implementation of the models, testing is an important part of the development of computer models. In the case of building energy modeling, these validation tests can be of three types:

- 1) comparison with experimentally-validated, analytically-computed results.
- 2) comparison with results of another validated computer model.
- 3) comparison with experimental results.

All of the element airflow equations, and wind and stack pressure models used in the Network program are derived based on either fundamental concepts or the results of experiments conducted by different researchers. Also, experimental results for all the complex networks tested here are not available. Therefore, this thesis concentrates only on the first two types of validation tests, i.e., analytical validation tests and comparison with other models (specifically, the Airnet model of Walton (1989) which is again an analytically validated model).

Apart from individual component models validation tests, the validation tests for ensuring the correctness of the system assembly and solution were also conducted on large and complex airflow networks involving a variety of flow elements. However only the validation tests for individual flow element models are presented here.

Crack Airflow Validation Tests

Validation tests for the crack airflow model were conducted using a simple four node network with three links in series. In these tests, series of different orifices ranging from 0.0001 m² to 1.0 m² in opening area were used for the middle opening; whereas the

areas of end openings remained the same (0.0001 m²) throughout. This can be considered as modeling two rooms having fixed openings on opposite sides connecting rooms to ambient conditions and a variable size opening inter-connecting the rooms. The driving force for airflow in the network is the pressure difference between the nodes 1 and 2 (an assumed value of 100.0 Pa). The discharge coefficient of all the openings is taken to be 0.6 i.e., the discharge coefficient for the sharp edged orifices (ASHRAE, 1989, Page 23.12)

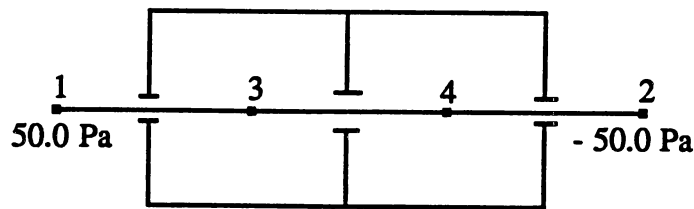


Figure 4.1 Network for Crack Airflow Validation Tests

On the network solution, the obtained flow rates were verified by comparing with those obtained analytically using an equivalent powerlaw coefficient for flows as follows:

$$\text{For airflow links in series } C_e = \frac{1}{\sqrt{\sum \frac{1}{C_{\text{LINK}}^2}}} \quad [4.1]$$

$$\text{Here } C_e = \frac{1}{\sqrt{\frac{1}{C_1^2} + \frac{1}{C_2^2} + \frac{1}{C_3^2}}} \quad [4.2]$$

$$\text{mass flow rate } \dot{m} = C_e \sqrt{\rho \Delta P} \quad [4.3]$$

C_1, C_2, C_3 = turbulent flow coefficients of links (link 1 connects node 1 to node 3; link 2 connects node 3 to node 4; link 3 connects node 4 to node 2)

C_e = turbulent flow coefficient of the equivalent link

ΔP = pressure difference between nodes 1 and 2 (Pa)

ρ = air density (kg/m³)

The following table gives the comparison of flow rates computed using an equivalent powerlaw coefficient, flow rates obtained from the Airtel model and the Network model. The Network model gave the expected results. Compared to analytical airflows calculated as above, the maximum variation in Network airflows was about 0.02%, and in Airtel airflows was about 0.03%.

TABLE I
CRACK AIRFLOW VALIDATION TEST RESULTS

| Opening Area (m ²) - (m ²) - (m ²) | Analytical Airflows (kg/s) | Airtel Airflows (kg/s) | Network Airflows (kg/s) |
|---|-------------------------------|---------------------------|----------------------------|
| 0.0001- 0.0001- 0.0001 | 0.00053772 | 0.00053758 | 0.00053763 |
| 0.0001 - 0.001 - 0.0001 | 0.00065692 | 0.00065676 | 0.00065684 |
| 0.0001 - 0.01 - 0.0001 | 0.00065855 | 0.00065839 | 0.00065847 |
| 0.0001 - 0.1 - 0.0001 | 0.00065856 | 0.00065840 | 0.00065848 |
| 0.0001 - 1.0 - 0.0001 | 0.00065856 | 0.00065840 | 0.00065848 |

Doorway Airflow Validation Tests

Buoyancy driven airflow across a doorway (of size 2.0m by 0.8m) connecting two zones maintained at different temperatures was modeled using the Network program. This simple network has the advantage of allowing a direct comparison to the correlation developed by Brown and Solvason (1962). The Brown and Solvason correlation is based on theoretical considerations similar to those used to develop the Network doorway model.

The correlation has been validated by Brown and Solvason with extensive experimental results.

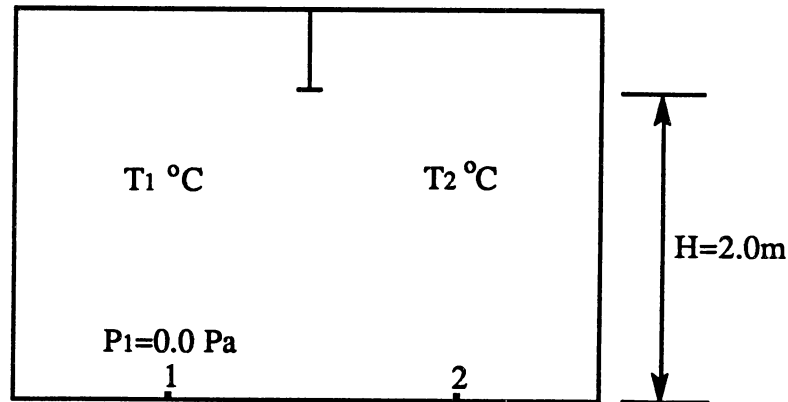


Figure 4.2 Network for Doorway Airflow Validation Tests

As discussed earlier in the chapter on Literature Review, Brown and Solvason have provided the following correlation using Nusselt number as a function of the Prandtl and the Grashof numbers for the phenomena of heat transfer through a doorway with the characteristic length taken to be the height of doorway.

$$Nu_H = \frac{C_D}{3} * Pr * \sqrt{Gr_H} \quad [4.4]$$

where $Nu_H = \frac{h * H}{k}$, $Pr = \frac{c_p * \mu}{k}$, and based on density difference $Gr_H = \frac{g * \rho * H^3 * \Delta\rho}{\mu^2}$

C_D = doorway discharge coefficient (in the range between 0.6 and 1.0)

μ = dynamic viscosity (kg/m-s)

ρ = average air density ($\rho_1 + \rho_2 / 2$ kg/m³)

$\Delta\rho = \rho_1 - \rho_2$ (kg/m³)

c_p = specific heat of air (J/kg-°C)

k = thermal conductivity of air (W/m-°C)

g = gravitational constant (9.8 m/s²)

h = convection heat transfer coefficient [$q/(W*H*\Delta T)$ W/m²-°C]

$\Delta T = T_1 - T_2$ (°C)

q = heat flux rate [$\dot{m}*c_p*\Delta T$ J/s]

H = doorway height (2.0 m)

W = doorway width (0.8 m)

\dot{m} = mass flow rate of air across the doorway (kg/s)

Upon substituting the above parameters into equation [4.4], the mass flow rate across doorway \dot{m} can be given as follows:

$$\dot{m} = \frac{C_D}{3} * W * \sqrt{\rho g \Delta \rho H^3} \quad [4.5]$$

In the first case airflow through the doorway was modeled using the Network doorway element model. The discharge coefficient (C_D) of doorway opening was taken to be 0.78 (Weber & Kearny, 1980).

In the second case the airflow through the doorway was modeled using an equivalent multiple opening model (this model was based on powerlaw relationship) consisting of 10 equal sized openings (each with dimension 0.2m x 0.8m, and discharge coefficient of 0.78). By setting the height of each "opening", the buoyant force at that level was accounted for.

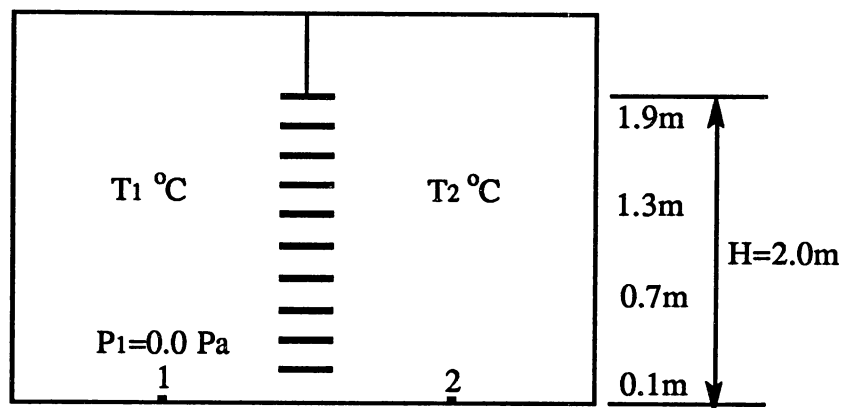


Figure 4.3 Doorway Modeled by Equivalent Multiple Openings

Table II summarizes the comparison of doorway airflow validation test results obtained from Brown and Solvason correlation (i.e., analytical airflows), Airtet model, Network doorway model and Network equivalent multiple opening model for a range of nodal temperature differential. The airflows presented in Table II are two-way airflows.

TABLE II
DOORWAY AIRFLOW VALIDATION TEST RESULTS

| Node 1 (°C) | Node 2 (°C) | Analytical Airflows (kg/s) | Airtet Airflows (kg/s) | Network Airflows Doorway Model (kg/s) | Network Airflows Multiple Opening Model (kg/s) |
|----------------|----------------|----------------------------------|------------------------------|---|--|
| 18 | 22 | 0.259057 | 0.259060 | 0.259075 | 0.260864 |
| 16 | 24 | 0.366388 | 0.366400 | 0.366420 | 0.368937 |
| 12 | 28 | 0.518296 | 0.518361 | 0.518389 | 0.521866 |

As compared to analytical airflows, the Network doorway element model airflows differ by less than 0.02%, and maximum variation in Network equivalent multiple opening model was less than 1.0%.

In addition, another test was conducted to verify the node-to-node flow directions in the top and bottom portions of the doorway on inter-changing the node temperatures. The flow directions were found to be physically correct and the results of this test are tabulated in Table III.

TABLE III
RESULTS OF DOORWAY AIRFLOW DIRECTION
VERIFICATION TESTS

| Case | Node Temp (°C) | | Flow Directions | |
|------|----------------|--------|-----------------|-------------|
| | Node 1 | Node 2 | Top Flow | Bottom Flow |
| 1 | 18 | 22 | 2 to 1 | 1 to 2 |
| 2 | 22 | 18 | 1 to 2 | 2 to 1 |

Duct Airflow Validation Tests

Two tests were conducted in order to validate the Network duct airflow element model. The first test uses a simple duct airflow network with three duct elements connected in series and the second test uses a network consisting of duct fittings.

In the case of the first test a network consisting of three serial duct elements of the same diameter, but of different lengths, connecting four nodes was modeled (Figure 4.4). The flow rates computed from the Network duct airflow model which is based on the Darcy-Weisbach equation with Altshul's explicit formulation for computing friction factor were compared with the flow rates obtained from the ASHRAE friction chart (ASHRAE, 1985, Page 33.26). Also the results were compared with the Airnet model of Walton (1989) which is based on Colebrook's implicit equation for computing friction factor.

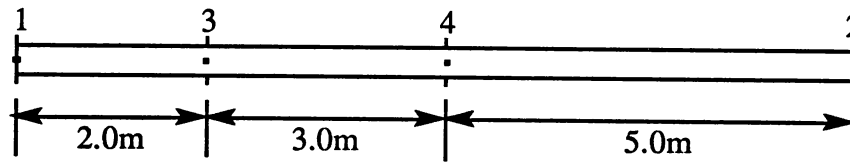


Figure 4.4 Network for Duct Airflow Validation Test #1

Here again two test cases using different duct diameters and frictional losses were carried out. In the first case, all ducts with diameter of 0.25 m, absolute roughness dimension of 0.15 mm, and frictional loss of 0.9 Pa/m (i.e., nodes 1 and 2 at 9.0 Pa and 0.0 Pa respectively) were chosen. The flow rate from the ASHRAE friction chart was 0.24 kg/s (at air density of 1.204 kg/m³) at a flow velocity of 4.0 m/s for this case. In the second case ducts all with diameter of 0.63 m, roughness dimensions of 0.15 mm, and frictional loss of 4.0 Pa/m (i.e., nodes 1 and 2 at 40.0 Pa and 0.0 Pa respectively) were chosen. In this case, the flow rate from ASHRAE friction chart was 6.0 kg/s at a flow velocity of 16.0 m/s. The frictional loss values chosen in both the above cases were within recommended range of frictional losses in duct designing.

The following table gives the comparison of results obtained from different sources. In both cases the Network airflows differ by less than 3% from those obtained from the ASHRAE friction chart.

TABLE IV
RESULTS OF DUCT AIRFLOW VALIDATION TEST #1

| Case | Duct Dia (m) | ASHRAE Flow (kg/s) | Airnet Flow (kg/s) | Network Flow (kg/s) |
|------|-----------------|-----------------------|-----------------------|------------------------|
| 1 | 0.25 | 0.24 | 0.245 | 0.243805 |
| 2 | 0.63 | 6.00 | 6.190 | 6.175761 |

In the case of second test a network consisting of a 90° elbow, two round ceiling diffusers, and a diverging 45° Wye with 45° elbow branching out from main by 90° was modeled. The network modeled for this test is shown in Figure 4.5. Nodes 1, 2, and 3 are constant pressure nodes respectively at pressures 50.0 Pa, 0.0 Pa, and 0.0 Pa. The duct flow coefficients used in network data file for this test were obtained from McQuiston and Parker (1988), and ASHRAE Handbook of Fundamentals (ASHRAE, 1989, Chapter 32).

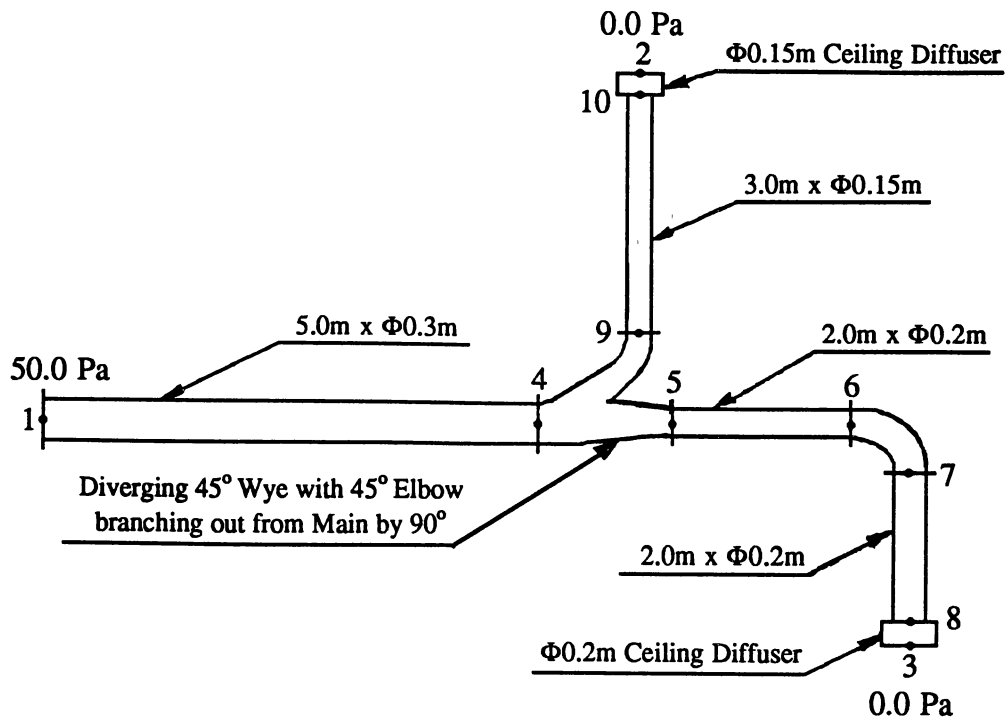


Figure 4.5 Network for Duct Airflow Validation Test #2

This test compares the pressure drops across various sections of the network obtained from the Network model with those calculated analytically. First the above network was modeled using the Network model. Then the airflow rates obtained from the Network model were used in analytical computation of pressure drops across the different sections of the network. Correspondingly these analytical pressure drops were compared with those obtained from the Network model. Table V summarizes this comparison.

TABLE V
RESULTS OF DUCT AIRFLOW VALIDATION TEST #2

| Network Section | Analytical ΔP (Pa) | Network ΔP (Pa) |
|-----------------|----------------------------|-------------------------|
| 1 - 4 | 2.151806 | 2.151044 |
| 4 - 5 | 1.047886 | 1.047698 |
| 5 - 6 | 2.678350 | 2.677658 |
| 6 - 7 | 2.561499 | 2.561133 |
| 7 - 8 | 2.678350 | 2.677797 |
| 8 - 3 | 38.888218 | 38.884670 |
| 4 - 9 | 6.723506 | 6.722347 |
| 9 - 10 | 6.457123 | 6.455880 |
| 10 - 2 | 34.672476 | 34.670728 |

As compared to analytical pressure drops, the Network pressure drops differ by less than 0.05%. Furthermore as nodes 1, 2, and 3 are constant pressure nodes with pressures 50.0 Pa, 0.0 Pa, and 0.0 Pa respectively, the expected pressure drops in the ducting branches connecting node 1 to node 2, and node 1 to node 3 should be 50.0 Pa each. From the results indicated in Table V it can be seen that upon adding the corresponding pressure drops of individual sections of the network the expected pressure drop of 50.0 Pa is obtained in both the branches.

Fan Airflow Validation Tests

A simple network consisting of a constant power fan provided with inlet and outlet ducts of diameters 0.25m and 0.2m respectively was modeled. The fan power was 1.0 hp, and nodes 1 and 2 were constant pressure nodes (both assumed to be ambient nodes at pressure 0.0 Pa).

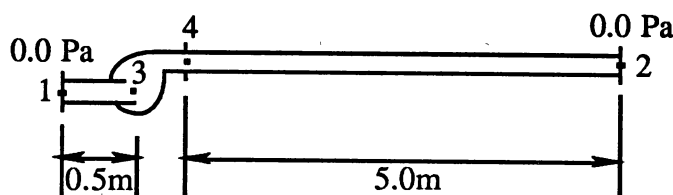


Figure 4.6 Network for Fan Airflow Validation Tests

Upon solution, the Network fan element model gave a flow rate of 1.639376 kg/s from node 3 to 4 at a pressure rise ($P_4 - P_3$) of 547.637770 Pa across the fan. On comparing the results with the Airnet model of Walton for the same network, the flow direction was found to be reversed (i.e., from node 4 to 3) and also the airflow rate across the fan was observed to be quite different.

Further tests were made and it was concluded that the Airnet program has a bug and cannot at this time correctly model a constant power fan.

Logically, the flow direction as obtained from the Network fan model is correct. Apart from this, the flow rate and pressure rise across the fan from the Network fan model were verified by back substitution into the constant power fan airflow equation and the expected fan power of 1.0 hp was obtained, thus ensuring the correct implementation of the constant power fan model in the Network program.

Stack Pressure Validation Tests

A simple two node network with buoyancy driven airflow was modeled. The two nodes were connected with two orifices of the same area (0.0025 m²), one at 0.0m height and another at 5.0m height from the reference node height. The stack pressure and flowrates obtained by the Network model were compared with those computed by using the following standard equation for stack pressure (Klote and Fothergill, 1983):

$$\Delta P = \frac{g P}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) h \quad [4.6]$$

g = gravitational constant (9.8 m/s²)

P = absolute pressure (101325.0 Pa)

R = gas constant for air (287 J/kg-K)

T_1, T_2 = absolute temperatures of node 1 and 2 (K)

h = distance above neutral plane (m)

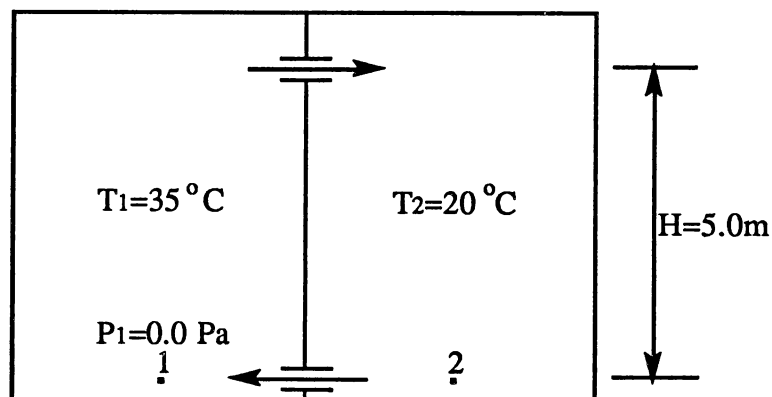


Figure 4.7 Network for Stack Pressure Validation Tests

As the sizes of both openings are same, the height of the neutral plane is 2.5m.

Upon substitution in equation [4.6]:

$$\begin{aligned}\Delta P &= 3459.878 \left(\frac{1}{293.15} - \frac{1}{308.15} \right) 2.5 \\ &= 1.436283 \text{ Pa}\end{aligned}$$

Using above pressure drop, the analytical airflow rate calculated from the powerlaw equation is 0.002790 kg/s. Network model computed a flow rate of 0.002755 kg/s across the openings at pressure drops of -1.400632 Pa and 1.472320 Pa for the lower and upper openings respectively. The average pressure drop between the nodes on neglecting signs is 1.436476 Pa. As compared to flow rate obtained from Klote and Fothergill equation, the Network flowrate differ by less than 1.5%.

Wind Pressure Validation Tests

The Network model requires a pressure coefficient data file for converting environmental parameters, such as wind speed and wind direction, to building surface pressure. The following wind pressure tests were conducted to ensure the proper conversion. A network consisting of two links having the same opening areas (0.01m²) connecting three nodes in series was modeled.

In Figure 4.8, node 1 is an ambient node, node 2 is a constant pressure node (0.0 Pa) and node 3 is a unknown pressure node. Based on Swami and Chandra (1988) model, for node 1 the pressure coefficient is equal to the product of 0.6 and cosine of the angle between normal to the wall and wind direction. For constant pressure node 2, all pressure coefficients are zero, and hence the pressure is fixed to be 0.0 Pa. Wind pressure on node 1 can be analytically computed using the relation:

$$P = C_p \frac{\rho V^2}{2} \quad [4.7]$$

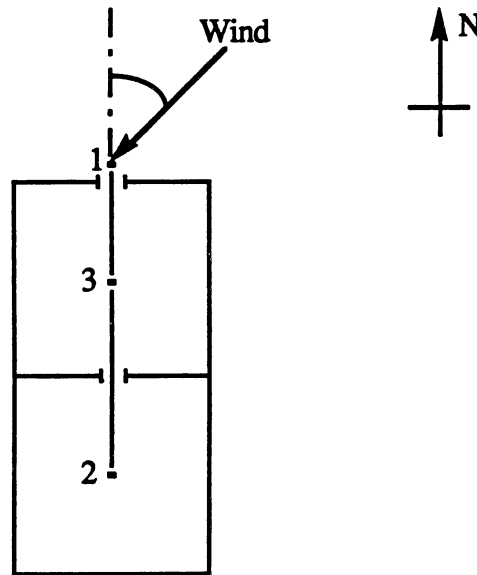


Figure 4.8 Network for Wind Pressure Validation Tests

For 0.0° wind direction, the pressure coefficient C_p for node 1 is 0.6. On substituting air density $\rho = 1.20415 \text{ kg/m}^3$, $C_p = 0.6$ and an assumed wind velocity $V = 4.15 \text{ m/s}$ in equation [4.7], the wind pressure on node 1 is 6.221542 Pa. Making use of an equivalent powerlaw flow coefficient, the flow rate computed analytically from the powerlaw relation is 0.016423 kg/s for this case. The flowrate obtained from the Network wind pressure model was also 0.016423 kg/s.

Similar tests were conducted for wind angles in the range of 0.0° to 180.0° . The test results are tabulated in Table VI. Slight difference between the analytical and Network pressures and flow rates for intermediate wind angles (i.e., angles other than 0.0° , 90.0° , and 180.0°) are due to two reasons. One reason is the truncation error in pressure coefficients in the input data file and another is the linear interpolation of the coefficients for intermediate wind angles. However, as compared to analytical results, the Network flow rates and node pressures differ by less than 1.0% and 2.0% respectively.

TABLE VI
WIND PRESSURE VALIDATION TEST RESULTS

| Wind Direction (deg) | Pressure (Node 1) | | Flow (Node 1 to Node 2) | |
|-------------------------|--------------------|-----------------|-------------------------|-------------------|
| | Analytical (Pa) | Network (Pa) | Analytical (kg/s) | Network (kg/s) |
| 0.0 | 6.221542 | 6.221533 | 0.016423 | 0.016423 |
| 30.0 | 5.388013 | 5.298326 | 0.015283 | 0.015155 |
| 60.0 | 3.110771 | 3.053736 | 0.011612 | 0.011506 |
| 90.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 120.0 | -3.110771 | -3.053736 | -0.011612 | -0.011506 |
| 150.0 | -5.388013 | -5.298326 | -0.015283 | -0.015155 |
| 180.0 | -6.221542 | -6.221533 | -0.016423 | -0.016423 |

Validation Tests for the Model Implementation into BLAST

These tests were conducted to ensure that the Network model is correctly implemented into the voluminous BLAST program and that there are no coding or linking errors.

The test house used for these tests is described in Appendix D. Only the living space of the test house was conditioned, and a constant temperature of 21.12 °C was maintained in the living space.

The zone loads with and without infiltration into the living space for a summer design day (Jul 21) for any particular hour (say 15:00) as obtained from BLAST program were compared. When there was no infiltration in the conditioned space, the cooling load

was 3.617 kwh. In the second case, with an infiltration rate of 0.150095 kg/s into the conditioned space (infiltration rate computed by the Network model), the cooling load was 5.624 kwh, and the infiltration heat gain was 2.008 kwh.

The infiltration heat gain for a given hour can be analytically computed using the relation:

$$Q_{inf} = \dot{m}_{inf} * C_p * (T_{amb} - T_{zone}) \quad [4.8]$$

\dot{m}_{inf} = infiltration rate (kg/s)

T_{amb} = ambient air temperature (°C)

T_{zone} = zone air temperature (°C)

At 15:00 hour

$$\begin{aligned} Q_{inf} &= 0.150095 * 1.004 * (34.444 - 21.12) \\ &= 2.0079 \text{ kwh} \end{aligned}$$

As mentioned earlier, BLAST gave an infiltration heat gain of 2.008 kwh for this test case. Furthermore, with no other changes in the test input except for infiltration, the cooling load for the conditioned space with infiltration should be equal to the cooling load without infiltration plus the heat gain only due to infiltration. Here, 3.617 kwh and 2.008 added together gives 5.625 kwh and the cooling load with infiltration as obtained from the BLAST program is 5.624 kwh. These results match each other.

The other remaining hours of the design day also showed similar agreement in the results ensuring the correct implementation of the Network model into the BLAST program.

Computation Time Tests

BLAST is a comprehensive building energy simulation program, and it works on an hour-by-hour basis. Hence, a significant amount of CPU time is required to perform yearlong simulations. So any routines that are to be implemented into the existing BLAST program are to be thoroughly tested for robustness and computation time requirements.

The computation time tests were conducted on the stand-alone version of the Network program on an Apollo workstation (series 400, 50 MHz, 68030 CPU). The program was compiled using an optimizing compiler.

As reported by many researchers, airflow networks have a reputation of slow convergence. Especially with a combination of very large and very small openings in the network, the convergence is slow requiring large number of iterations. The most crucial part in the Network model, as far as CPU time is concerned, is Newton's method, an iterative method for solution of nonlinear airflow equations. As discussed earlier in the Literature Review and Methodology, the pressure correction method has a significant effect on the convergence in Newton's method. The two main types of correction methods that were studied are the Steffensen iteration and the constant under-relaxation method.

Three different networks were tested for computation time requirements using a series of constant under-relaxation factors ranging from 0.1 to 1.0, and then using the Steffensen iteration. The first network had four ambient nodes, five unknown pressure nodes and ten links consisting of only crack elements whose areas ranged from as small as 0.0001 m² to as high as 1.0 m². In the second network, there were four ambient nodes, four unknown pressure nodes and eight links consisting of both crack and door elements. The third network had five constant pressure nodes (all at 0.0 Pa), nine unknown pressure nodes and thirteen links consisting of fan and duct elements. For the first and second networks the simulations were performed for 1000 hours with varying wind speeds and wind directions. In the case of third network, the simulations were performed with no wind pressure effect on the network by setting all surface pressure coefficients to zero in the data

file. As there was no wind effect, the computation time requirements were tested only for 100 hours in this case. In all the three cases, the absolute and the relative convergence criteria were chosen to be 0.000001 kg/s and 0.0001 respectively. The computation time requirements in minutes for simulation of each of these networks using different correction methods are tabulated in Table VII.

TABLE VII
COMPUTATION TIME TEST RESULTS

| Correction Method | Network #1 (For 1000 Hrs) (min) | Network #2 (For 1000 Hrs) (min) | Network #3 (For 100 Hrs) (min) |
|-------------------------------------|---------------------------------------|---------------------------------------|---|
| Constant Under Relaxation Method | | | |
| 0.1 | 16.75 | 10.92 | 6.43 |
| 0.2 | 8.22 | 5.20 | 5.83 |
| 0.3 | 5.45 | 3.38 | 2.48 |
| 0.4 | 3.97 | 2.47 | 2.43 |
| 0.5 | 3.83 | 1.92 | 1.87 |
| 0.6 | 2.50 | 1.45 | 1.00 |
| 0.7 | 2.33 | 1.32 | 2.50 |
| 0.8 | 1.80 | 1.23 | 3.28 |
| 0.9 | 1.68 | 1.25 | Solution did not converge in 1000 iterations |
| 1.0 | 1.87 | 2.83 | " |
| Steffensen Iteration Method | 1.27 | 1.17 | 0.85 |

In the case of constant under relaxation method with lower under relaxation factors, the corrections applied were small, and hence led to slow convergence of the solution. Gradually with the increase of the under relaxation factor the solution showed the tendency of faster convergence up to a certain point in all the three networks. Later the increase in the under-relaxation factor caused the occurrence of remarkable oscillating corrections. This again led to slower convergence of solution. Especially in the case of the third network, for the under-relaxation factor of 0.9 and above the solution did not converge at all in the first hour, even after 1000 iterations. This was due to oscillating pressure corrections never showing the tendency of convergence of solution.

However, in the case of Steffensen iteration, for all the three networks the solution converged faster compared to all other constant under-relaxation factor runs. Apart from this, Steffensen iteration also led to fastest convergence showing no tendency of interference with rapid convergence in a variety of other airflow networks tested by the author.

Attic Ventilation Tests

Increasing concern for reduction of energy costs and conservation of energy has given greater emphasis to the need for effective attic ventilation. The primary purpose of attic ventilation is to lower the attic temperature and reduce the heat flux from the attic to the living spaces below. The residential building construction industry has developed a variety of ventilation schemes for installation in attic space. Quantity and direction of airflow through attic space is greatly dependent on the type and location of vents used.

These tests were conducted to demonstrate the potential uses of the Network model in studying attic ventilation and ventilative cooling of structures. These tests were conducted on the same test house as described in Appendix D. Appendix D also provides the description of different attic ventilation schemes used in these tests. Here again only the

living space is conditioned and a constant temperature profile of 21.12 °C is specified for the conditioned space.

A variety of attic ventilation schemes were studied using the BLAST-coupled Network model for a design day (Jul 21) and for actual weather data (using TRY weather data file for Columbia, Missouri). These ventilation schemes include ridge-soffit, gable end, and powered ventilation. The effects of different ventilation schemes on living space attic temperature, building cooling loads, and also computation time requirements for annual simulation were studied. The purpose of these tests is not to decide which of the ventilative schemes is the best, but to demonstrate the effects of the size and location of ventilation openings on infiltration rates and subsequently the effect of infiltration on attic temperatures and building cooling loads. However, given a building and necessary input data, designers can use this model as a tool in investigating which ventilation scheme best suits the building HVAC design.

Because of the shortage of surface pressure coefficient data for ventilation openings at different locations of building envelopes (e.g., soffit vents, ridge vents etc.,) some educated guess work has been made in determining these pressure coefficients. Wiren (1985), Swami and Chandra (1988), and ASHRAE Hand Book of Fundamentals (ASHRAE, 1989, chapter 14), were referred to while preparing the surface pressure coefficient data files for these tests. Also, several other approximations were made in determining flow characteristics of various ventilation openings in the test house.

In the first case, living space attic temperatures were studied for design day weather with different ventilation schemes and later using actual weather data from the TRY weather data file for two consecutive days (i.e., Aug 21 and 22, 48 hours). In the second case, the effect of ventilation schemes on the annual cooling loads of the test house and execution time requirement for annual simulations (on the Apollo workstation) were studied.

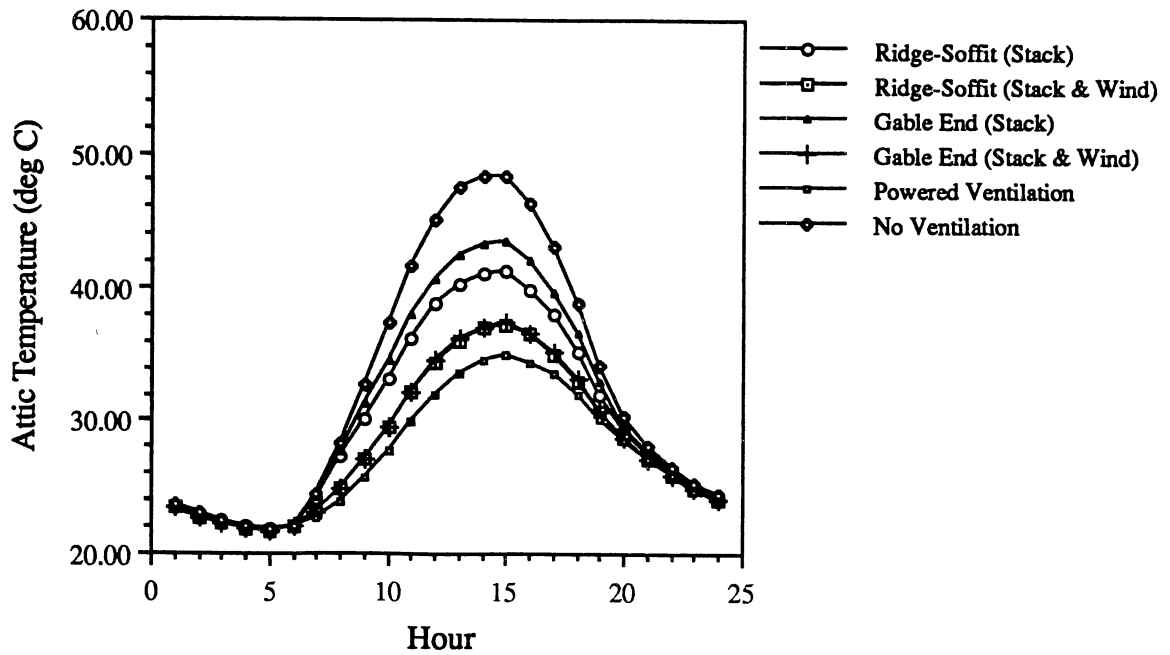


Figure 4.9 Hourly Living Space Attic Temperature Profile for Design Day (Jul 21)

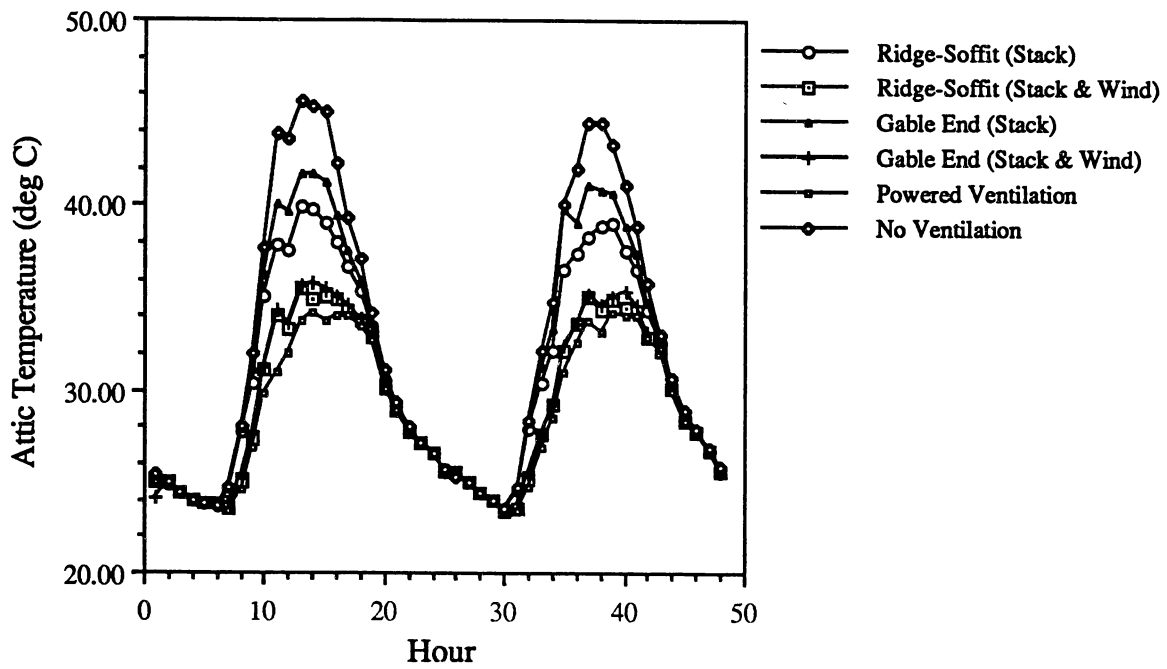


Figure 4.10 Hourly Living Space Attic Temperature Profile for Actual Weather Data (TRY Weather Tape Run for Aug 21 through Aug 22)

Figures 4.9 and 4.10 plot the hourly living space attic temperature of the test house for different ventilation schemes. For comparison purposes, the ridge-soffit scheme and gable end scheme were modeled with and without wind effects.

The attic temperatures went as high as 48.28 °C on the design day in the case of no attic ventilation as compared to 34.87 °C in the case of powered attic ventilation and 37.17 °C in the case of ridge-soffit ventilation (with wind and buoyancy driven airflows), thus demanding more energy for cooling the living space below.

Figure 4.11 is the plot of annual cooling load for the test house for different ventilation schemes:

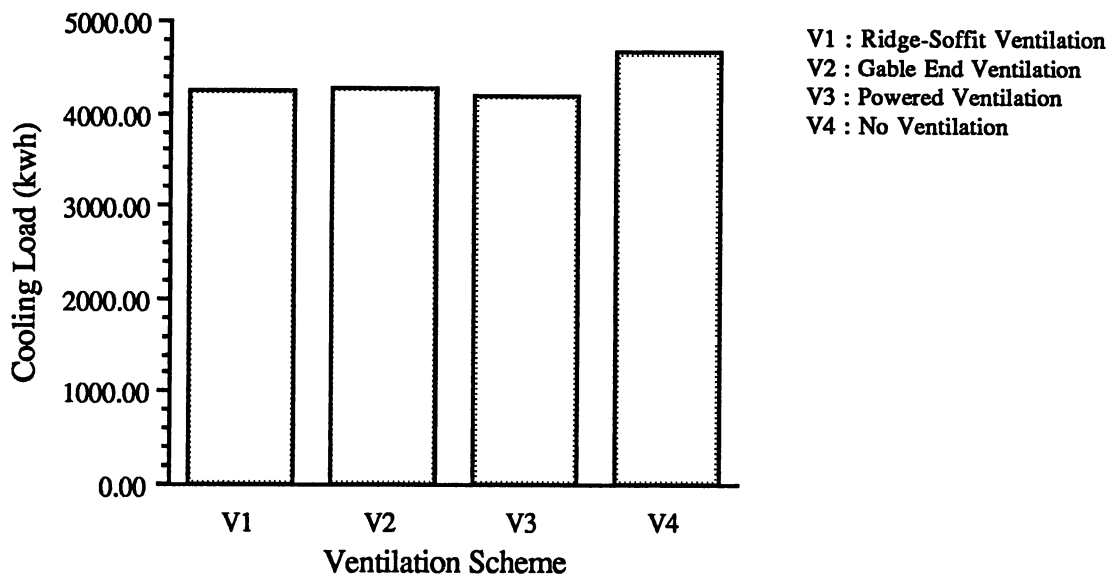


Figure 4.11 Plot of Annual Cooling Load

As compared to no attic ventilation, the reduction in cooling load using powered attic ventilation was about 11%, and using ridge-soffit ventilation was about 9%. Gable

end ventilation resulted in 8.5% reduction in cooling load compared to no attic ventilation. This indicates the significance of attic ventilation in reducing annual HVAC energy costs.

The plot of execution time required by the BLAST coupled Network program for annual simulation of building energy is shown in Figure 4.12.

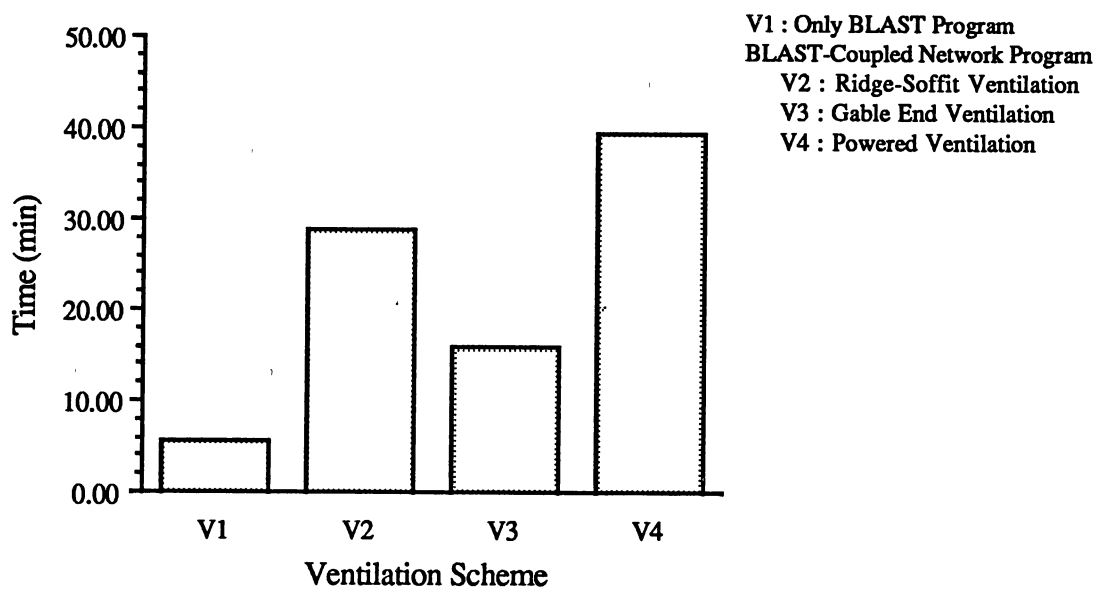


Figure 4.12 Plot of BLAST Execution Time for Annual Building Energy Simulation

There is a sizable increase in BLAST execution time with the implementation of the Network model. However this additional computation time may be justified in many situations, including detailed building energy analysis, designing effective building ventilation schemes, zone thermal comfort studies, and indoor quality and contaminant transport modeling.

Thermal Comfort Tests

The BLAST program has three Thermal Comfort models. These are the Fanger, KSU and Pierce comfort models, all of which are well recognized models in ASHRAE literature. They apply an energy balance to a person and use the energy exchange mechanisms along with experimentally derived physiological parameters to predict the thermal sensation and the physiological response of a person due to the environment. These models differ from each other in the criteria used to predict thermal sensation and also in the physiological models such as human neural control system for through-from body heat transfer, sweating, shivering and skin blood flow.

As a test case in thermal comfort studies, Arens et al. (1984) have modeled natural ventilation and described a procedure for predicting thermal comfort of people in naturally ventilated buildings. They have used modified outdoor climate (such as wind and temperature) for prediction of indoor climate. For air velocity, the modification was performed using velocity ratios obtained from wind tunnel tests of the buildings. The indoor temperatures were predicted based on the extent to which the buildings were ventilated.

Thermal comfort studies were conducted using the BLAST-coupled Network model and the effects of natural ventilation on Predicted Mean Vote (PMV), which is an index of zone thermal comfort, were studied. PMV is a complex mathematical function of human activity level, clothing, air temperature, mean radiant temperature, relative air velocity, and air humidity. The positive value of PMV is an indication of warmer conditions, and the negative value is an indication of colder conditions. PMV around zero is an indication of conditions most likely to be considered comfortable by occupants.

Air velocity at the occupants location is the appropriate velocity to be used in the prediction of zone thermal comfort and it depends on the quantity and direction of airflow, location of persons in the zone, zone volume, etc. The prediction of thermal comfort using local air velocities is highly impractical because the local air velocities differ remarkably for

each point in the zone. However several approximations can be utilized for this purpose such that reasonable computation time is required.

Currently BLAST has no facility to compute the hourly air velocities based on actual building airflows and it does the thermal comfort calculations using a constant air velocity specified by the user for each zone in the input file. In spite of these drawbacks as of today BLAST is the only building energy analysis program capable of doing thermal comfort simulations.

To add to the further usefulness of the BLAST thermal comfort modeling capabilities, tests were conducted in an expedient fashion to study the effect of building airflows on thermal comfort. These tests were conducted by separately incorporating the facilities into the BLAST-coupled Network model to calculate the hourly inlet air velocities (velocities at the ventilation inlets of a zone) and hourly bulk air velocities in the zone based on the actual building airflows.

The same test house described in Appendix D was used for these thermal comfort tests. The location of test house was again Columbia, Missouri. The other input parameters include five persons inside the conditioned zone (i.e., living space) with constant metabolic rate of 1.0 met (i.e., 58.2 W/m² which corresponds to metabolic heat generation of a person doing light office activity) and constant clothing insulation of 0.5 clo (i.e., 0.0775 m²-°C/W which correspond to normal clothing). A constant value of 0.4 was considered for relative humidity of air. There was no mechanical cooling and living space cooling was only possible due to ventilation. The living space was provided with two equal sized ventilation openings on opposite sides of the test house (each on north and south walls) for this purpose as shown in Figure 4.13.

The Fanger comfort model was selected for these studies. A report containing the thermal comfort output was generated by specifying the name of thermal comfort model selected in a reports statement of BLAST input file as follows: REPORTS (FANGER). Currently in the BLAST program the thermal comfort reports are only valid for design day

runs and not for weather tape runs. (Monthly summaries for weather tape runs have been added in the recently released version.) However, a single day weather tape run for Jul 21 was temporarily made possible here in these tests by suitably modifying the "SUDDEN" routine (grouped under "rout8.ftn") of BLAST to set up a design day with actual weather data obtained from the TRY weather tape for Jul 21. (The SUDDEN routine in the BLAST program sets up 24 hours of weather data from the user specified parameters).

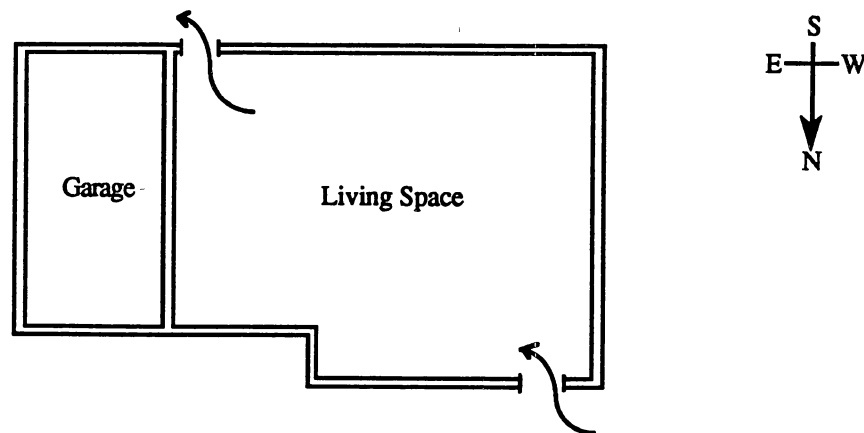


Figure 4.13 Ventilation Openings in the Test House for Thermal Comfort Studies

The tests were conducted by changing the area of the ventilation openings ranging from 0.01 m² to 1.0 m². Also a case with no ventilation was tried. The effects of these changing ventilation on hourly zone air temperatures, inlet and bulk air velocities, and thermal comfort (PMV) were studied.

Knowing the airflow rate, opening area and air density the inlet air velocity at the ventilation inlets can be calculated, whereas room bulk air velocity \bar{V} can be estimated using correlations (Equations 4.9 and 4.10) developed by Spitler (1990).

$$\text{For Ceiling inlet : } \bar{V} = 0.344 * J^{0.5} \quad [4.9]$$

$$\text{For wall inlet : } \bar{V} = 0.394 * J^{0.5} \quad [4.10]$$

where J is jet momentum number which can be calculated as follows,

$$J = \frac{\dot{m} U_o}{\rho g V_{\text{room}}} \quad [4.11]$$

where \dot{m} = mass flow rate of air (kg/s)

U_o = inlet air velocity (m/s)

ρ = room air density (kg/m³)

g = gravitational constant (m/s²)

V_{room} = room volume (m³)

Figure 4.14 is the plot of hourly variation in environmental parameters (wind speed and wind direction) on Jul 21 as reported by the TRY weather tape for Columbia, Missouri.

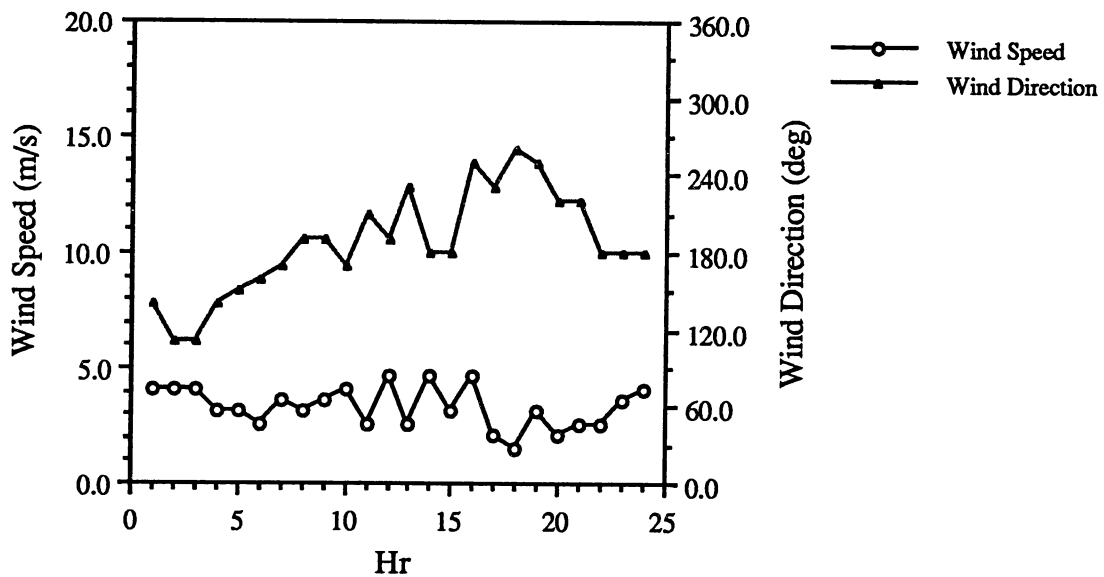


Figure 4.14 Plot of Hourly Wind Speed and Wind Direction on Jul 21 in Columbia, Missouri from the TRY Weather Tape

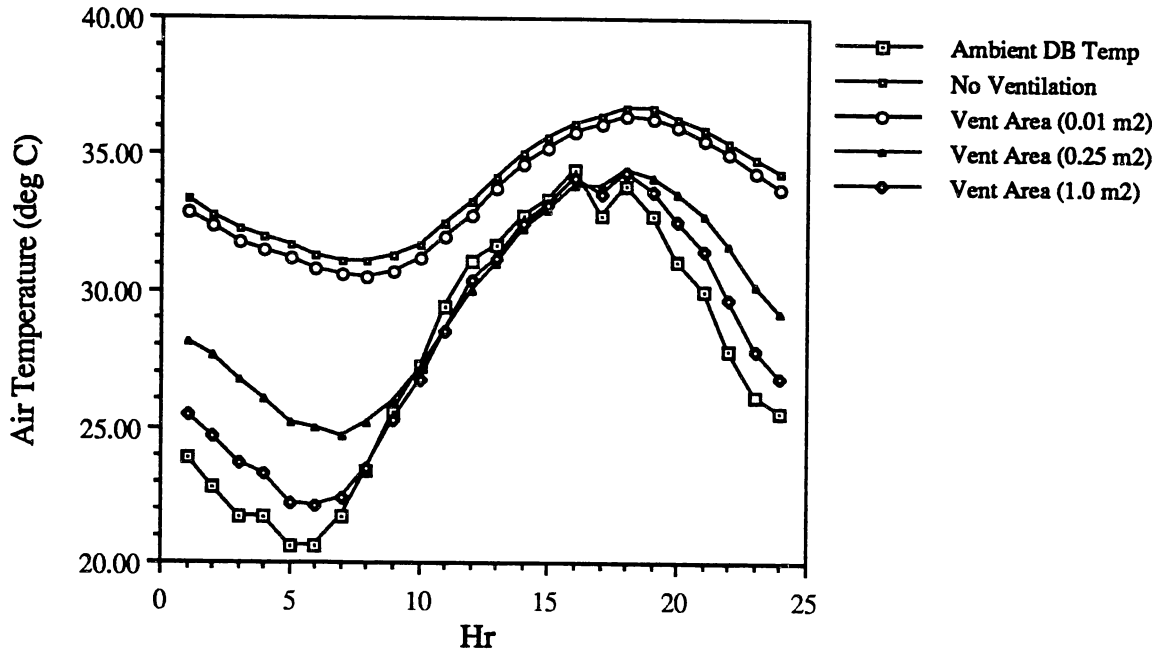


Figure 4.15 Plot of Hourly Ambient Dry Bulb and Living Space Air Temperatures

Figure 4.15 is the plot of hourly ambient dry bulb and living space mean air temperatures. For no ventilation the living space temperatures were highest for all the hours. With the increase in ventilation, the hourly living space temperatures gradually approached ambient temperatures providing cooler temperatures inside the living space.

Figure 4.16 and 4.17 present the plots of hourly bulk and inlet air velocities respectively for different vent areas. The results indicate that compared to inlet air velocities, the bulk air velocities are too small for the same vent areas and flow rates. This is because of the large volume of the living space which was taken into account in bulk air velocity computations.

The plots of hourly Predicted Mean Vote indicating the thermal comfort status of the living space for different ventilation opening areas based on bulk and inlet air velocities are presented in Figures 4.18 and 4.19 respectively.

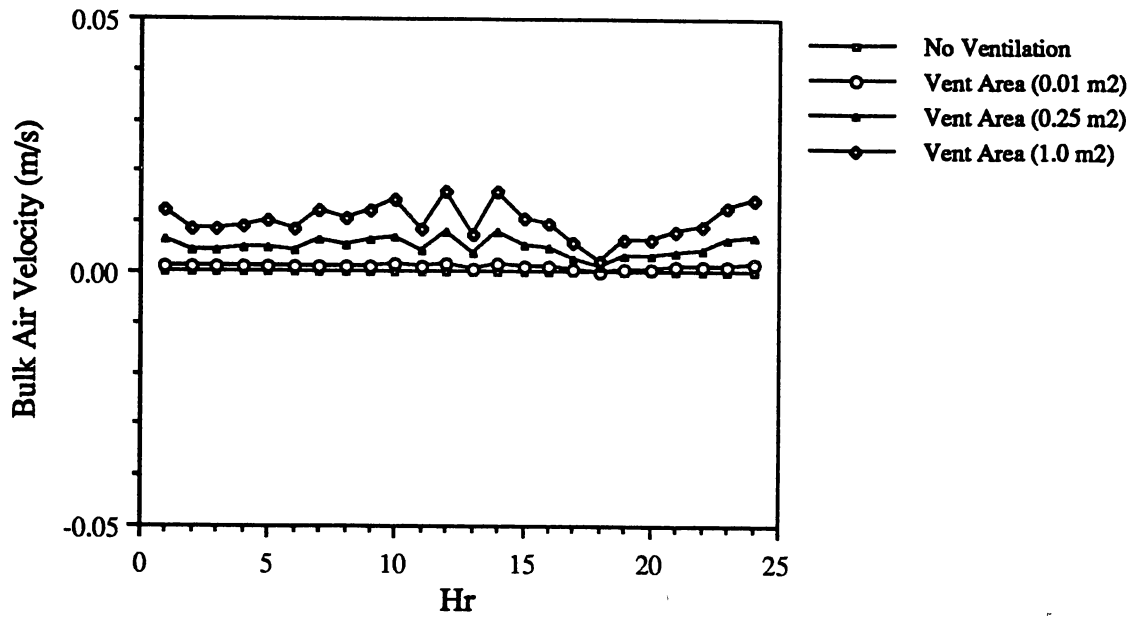


Figure 4.16 Plot of Hourly Bulk Air Velocity in the Living Space

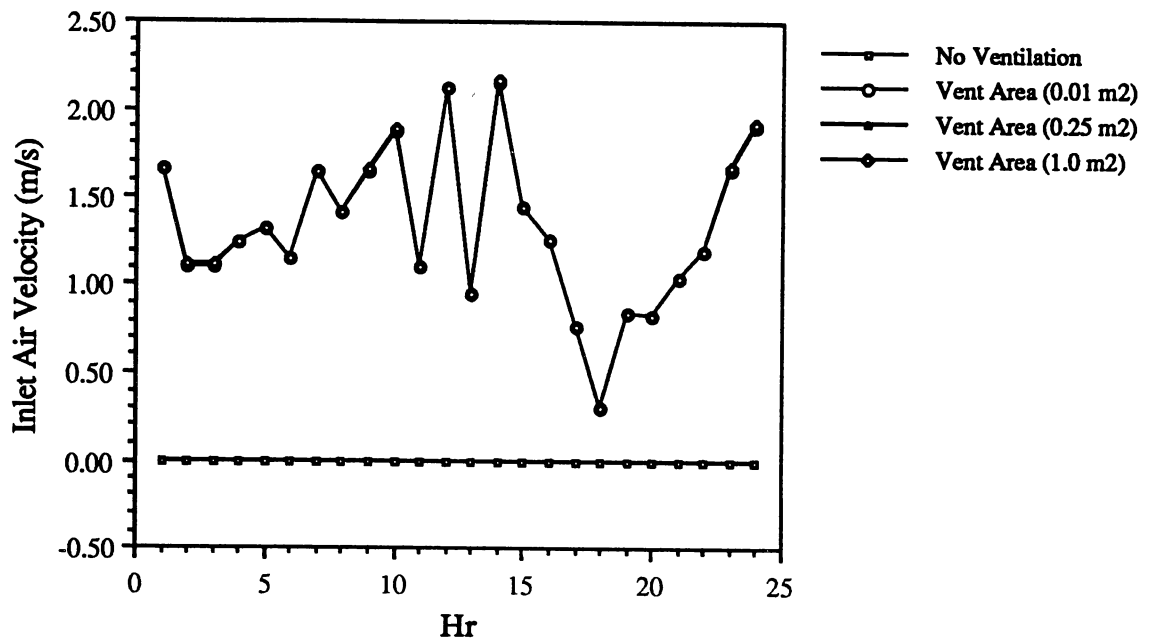


Figure 4.17 Plot of Hourly Inlet Air Velocity at the Ventilation Inlet

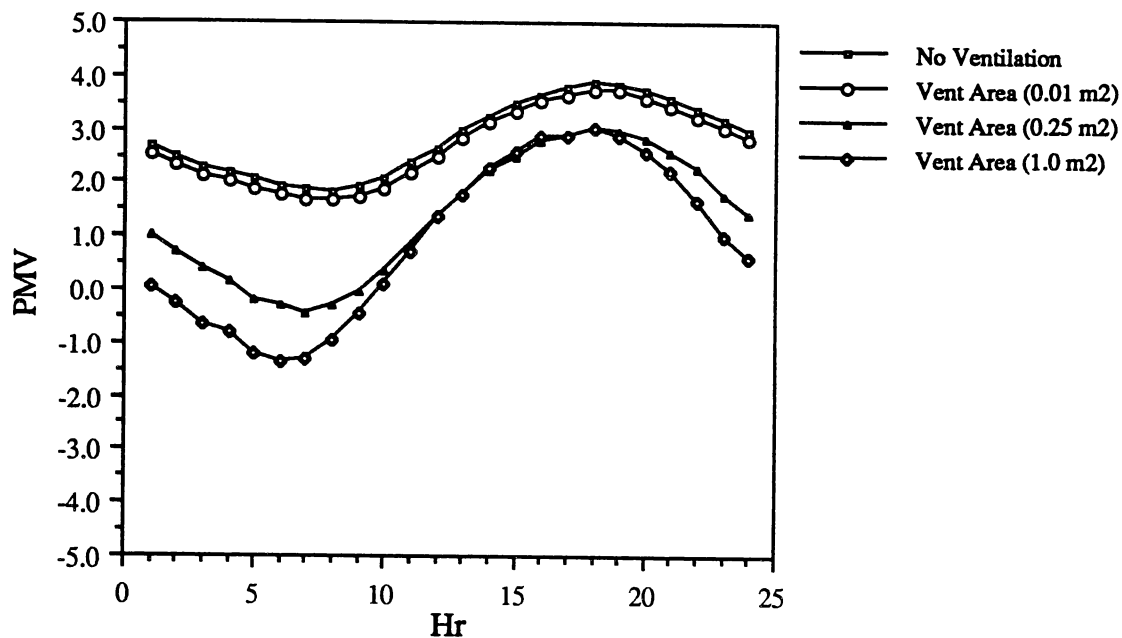


Figure 4.18 Plot of Hourly PMV for the Living Space (Based on Bulk Air Velocity)

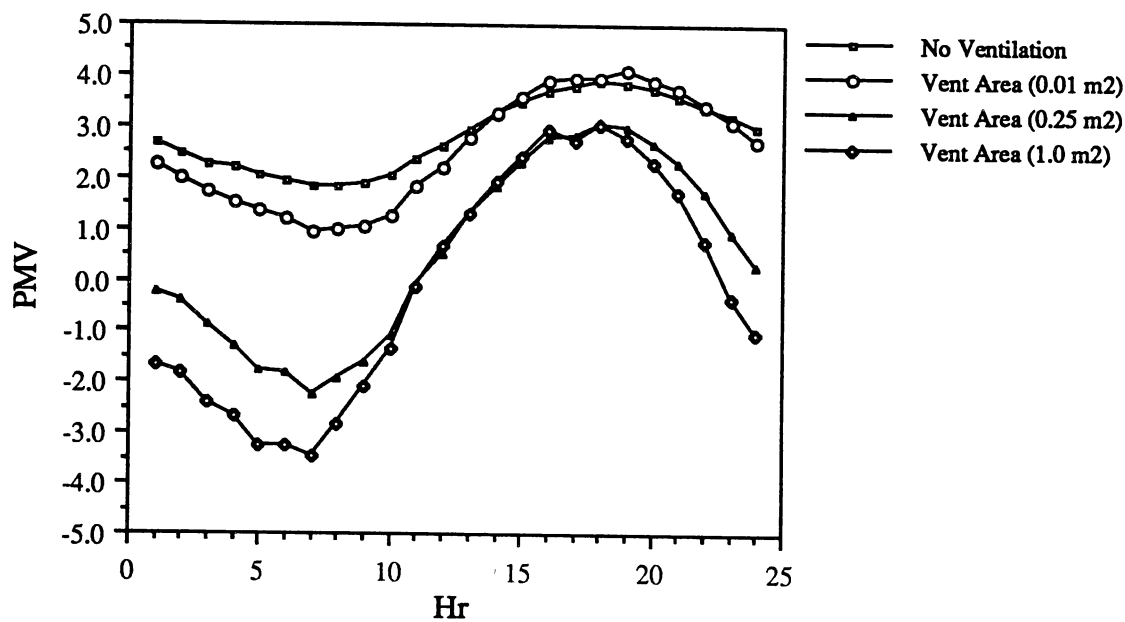


Figure 4.19 Plot of Hourly PMV for the Living Space (Based on Inlet Air Velocity)

From the plots it can be seen that during the hours 13:00 to 21:00, the PMV values corresponding to the bulk and inlet air velocities are close to each other indicating a small influence of air velocity on PMV when there are higher temperatures in the living space. However at lower living space temperatures, the air velocity has a significant influence on the PMV.

Generally, local air velocity at a point in a room lies somewhere between the bulk and inlet air velocities depending on the location of the point in the room (i.e., how far is the point from the ventilation inlets and in what direction, etc.). The use of either bulk or inlet air velocity is a simple approximation for local air velocity. Another approximation for local air velocity may be the use of weighted averages of bulk and inlet air velocities accounting for volume contents of the zone, location of persons and distribution of ventilation openings in the zone.

However, the extent of error induced by the use of above approximations for local air velocities in the prediction of PMV needs further investigation before any of these can be used extensively in thermal comfort analysis.

From the previous plots it can be seen that with no ventilation in the living space, the hourly mean air temperatures were high in the space and the air velocities were zero, thus leading to hotter conditions inside the space throughout the day. All hourly PMV values above zero clearly indicate this. However with larger ventilation rates (i.e., with 1.0 m² ventilation opening) the daytime hours were hotter and the nighttime hours were accompanied by colder conditions. This is due to large amount of heat energy added and taken away by the ventilating air during day and nighttime hours of the day respectively. For an intermediate ventilation opening area of 0.25 m², on an average the living space thermal comfort conditions were comparatively better.

All these tests demonstrate the potential applications of the Network model in detailed building energy analysis, ventilative cooling studies, and prediction of thermal comfort.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The conclusions that can be drawn from the previous chapters, and the recommendations for future work and improvements are summarized in this chapter.

Conclusions

1) Performance of the Network model studied by conducting a variety of tests indicated that the detailed analysis of building airflows is a practical possibility given adequate knowledge of building surface pressure coefficients and element flow parameters. The yearlong simulation of building airflow networks on an hourly basis for use in energy analysis is also feasible.

2) Implementation of the Network model into the BLAST program has increased the usefulness of BLAST, particularly for cases where ventilation and/or interzone airflows have a significant effect on the thermal balance.

3) The following flow element models have been implemented into the Network program: cracks, doorways, ducts and fans. The duct and fan models can be used in the analysis of duct airflows in building HVAC systems.

4) Of all the pressure correction methods tried in the Newton's method for solution of nonlinear airflow equations, the Steffensen iteration led to the fastest convergence in all the cases examined.

5) Potential applications of the Network model include:

- i) Modeling attic ventilation and ventilative cooling of structures.
- ii) Predicting zone thermal comfort.

iii) Modeling of contaminant transportation for predicting indoor air quality.

Though at present BLAST is the only detailed building energy analysis program capable of doing thermal comfort simulations, it did not previously have capability to compute the hourly air velocities in the zones based on the building airflows, rather users were required to specify air velocities for each zone in the input file. The implementation of the Network model (provided with routines to calculate hourly air velocities based on the building airflows) adds to the further usefulness of the BLAST program in predicting zone thermal comfort.

Recommendations

Several recommendations can be made for future research work. These include studying innovative ventilative cooling strategies and modeling of contaminant transportation to predict indoor air quality.

1) The term ventilative cooling means either bringing in ventilation air to directly cool occupants or bringing in ventilation air at night to cool the building structure so as to reduce daytime cooling loads. The concept of nighttime ventilative cooling has become a topic of increased interest in recent years.

The ventilative cooling studies done so far have been limited by the convection models available. The most significant aspect in the analysis of nighttime ventilative cooling of building structures is establishing energy coupling between the room air and the room surfaces i.e., convection heat transfer. Currently, most building energy analysis programs use the well-stirred model. The well-stirred model assumes that the zone air has uniform temperature and the convection heat transfer coefficients can be selected accordingly to predict the convection heat transfer. These assumptions have been questioned by numerous researchers and the recent experimental studies confirm that this model can severely underpredict convection heat transfer under ventilative cooling conditions (Spitler, 1990).

Spitler (1990) has successfully correlated the film coefficients to jet momentum number J (defined in Chapter IV) using a correlation of the form:

$$h = C_1 + C_2 * J^{0.5}$$

where h is the film coefficient ($W/m^2 \cdot ^\circ C$), and C_1 and C_2 are empirically determined correlation coefficients.

In addition to the above, Spitler (1990) has a more extensive and detailed literature review pertinent to ventilative cooling. Based on these guidelines and correlation available, algorithms for determining the convective heat transfer coefficient as a function of geometry, jet momentum number (J), and surface orientation can be developed. This can serve as an improved convective heat transfer model for use in the analysis of ventilative cooling strategies. Further studies can be conducted to investigate the interaction between convective heat transfer and the rest of building energy simulation in a more thorough manner. This convection heat transfer model in combination with the Network model and a model for prediction of exterior pressure distribution could be an appropriate simulation tool capable of modeling simultaneously all aspects of ventilative cooling of structures.

2) Indoor air quality in residences, offices, and other environments is a concern. Modeling of indoor air quality has gained importance in recent years with the rise of the phenomena known as Sick Building Syndrome. Contaminants that present particular problems in the indoor environment include dusts, tobacco smokes, fumes, toxic gases, mist, fog, etc., mostly originating from numerous areas of human activity. Ability to model interzone airflows is an important step towards developing indoor air quality and contaminant transportation models.

The structure of the Network model is devised in a very flexible way such that any future addition and development in the model should require minimal modifications in the

basic structure of the program. Contaminant transportation models can be developed and integrated with the Network model for predicting indoor air quality.

3) As a first step towards examining the potential uses of the BLAST-coupled Network model in thermal comfort analysis, the routines for computing air velocity (i.e., approximation to local air velocity) were implemented in a very expedient fashion. However better techniques for this purpose can be devised and implemented into the model.

4) The available surface pressure coefficient database for buildings is very limited. Especially in the area of roof slopes and complex building shapes there is a remarkable shortage of C_p data. The uncertainty in the input parameters will limit the accuracy of building airflow calculations. Experimental investigation of surface pressure coefficients for complex building shapes and roof slopes by conducting wind tunnel tests is recommended. Also it may be possible to determine pressure coefficients with Computational Fluid Dynamics techniques.

5) The physical characteristics of flow for a variety of flow elements and flow paths need to be investigated and mathematical formulation of these flows need to be devised so as to enable analysis of airflow through any type of flow path in buildings.

6) Although a variety of tests were conducted using the Network model and the results look very promising, some important questions remain. These are the reliability of flow equations and the network solution techniques. They are to be thoroughly investigated and experimentally validated before the Network model can be used extensively in building energy analysis. Further research is needed in determining the most reliable and accurate airflow network solution method. More sophisticated flow formulations and solution algorithms could result from further research in mathematical analysis of the network flow equations and from experimental validation of the simplifying assumptions in the airflow element models and solution method.

7) Additional recommendations can be suggested to improve the Network model and make the software more flexible and easier to use.

- i) The program can be modified so that it can generate airflow network and surface pressure coefficient data on its own, by adding parameters to the existing BLAST input file.
- ii) Model can be made more useful by adding features to schedule ventilation opening areas. This can serve as an essential feature in simulating an actual building in operation with varying ventilative flow areas during different seasons of an year and during different hours of a day.
- iii) Another potential improvement is to allow some control of opening area based on zone temperature or thermal comfort.
- iv) The sparse matrix techniques can be incorporated in the network solution routines of the program for solving the simultaneous equations involving Jacobian matrix. This feature allows bigger networks and larger system of equations to be handled without an execution time penalty for using the complete matrices.
- v) A more user-friendly user interface can be provided for the program.

BIBLIOGRAPHY

- Akins, R. E., J. A. Peterka, and J. E. Cermak. 1979. "Averaged Pressure Coefficients for Rectangular Buildings", Proceedings of the Fifth International Conference on Wind Engineering, Fort Collins, Colorado. July.
- Allard, F. and M. Herrlin. 1989. "Wind-Induced Ventilation", ASHRAE Transactions, Vol. 95, Part 2.
- Arens, E. A., A. G. Blyholder, and G. E. Schiller. 1984. "Predicting Thermal Comfort of People in Naturally Ventilated Buildings", ASHRAE Transactions, Vol. 90, Part 1B
- ASHRAE. 1983. "ASHRAE Handbook - 1983 Equipment", American Society of Heating, Refrigeration, and Air-Conditioning Engineers Inc., Atlanta, Georgia.
- ASHRAE. 1985. "ASHRAE Handbook - 1985 Fundamentals", SI Edition, American Society of Heating, Refrigeration, and Air-Conditioning Engineers Inc., Atlanta, Georgia.
- ASHRAE. 1989. "ASHRAE Handbook - 1989 Fundamentals", SI Edition, American Society of Heating, Refrigeration, and Air-Conditioning Engineers Inc., Atlanta, Georgia.
- Aynsley, R. M. 1988. "A Resistance Approach to Estimating Airflow Through Buildings With Large Openings Due to Wind", ASHRAE Transactions, Vol. 94, Part 2.
- Aynsley, R. M. 1989. "The Estimation of Wind Pressures at Ventilation Inlets and Outlets on Buildings", ASHRAE Transactions, Vol. 95, Part 2.
- Baker, P. H., S. Sharples, and I. C. Ward. 1987. "Air Flow Through Cracks", Building and Environment, Vol. 22, No 4, Pergamon Press, Oxford, UK.
- Barakat, S. A. 1987. "Inter-Zone Convective Heat Transfer in Buildings: A Review", Journal of Solar Energy Engineering, ASME, Vol. 109, May.
- Bilsborrow, R. E. and F. R. Fricke. 1975. "Model Verification of Analogue Infiltration Predictions", Building Science, Vol. 10, Pergamon Press, Oxford, UK.
- BLAST Support Office. 1986. "BLAST 3.0 User's Manual", University of Illinois at Urbana-Champaign, Urbana, Illinois.
- Blevins, R. D. 1984. "Applied Fluid Dynamics Handbook", Van Nostrand Reinhold Company Inc, New York.

- Brown, W. G. and K. R. Solvason. 1962. "Natural Convection Through Rectangular Openings in Partitions -1: Vertical Partitions", International Journal of Heat and Mass Transfer, Vol. 5, Pergamon Press, Oxford, UK
- Byrne, G. D. and C. A. Hall. 1973. "Numerical Solution of Systems of Nonlinear Algebraic Equations", Academic Press, New York.
- Carrier, W. H., R. E. Cherne, W. A. Grant, and W. H Roberts. 1959. "Modern Air Conditioning, Heating, and Ventilating", 3rd Edition, Pitman Publishing Corporation, New York.
- Chandra, S., P. W. Fairey, and A. Bowen. 1982. "Passive Cooling by Natural Ventilation: A literature Review", Report No. FSEC-CR-37-82 (EA), Florida Solar Energy Center, Cape Canaveral, Florida. January.
- Clarke, J. A. 1985. "Energy Simulation in Building Design", Adam Hilger Ltd., Bristol. ✓
- Conte, S. D. and C. de Boor. 1972. "Elementary Numerical Analysis: an Algorithmic Approach", McGraw-Hill, New York.
- Demuren, A. O. and F. J. K. Ideriah. 1986. "Pipe Network Analysis by Partial Pivoting Method", Journal of Hydraulic Engineering, ASCE, Vol. 112, No 5, May.
- Dhatt, G., G. Touzot, and G. Catin. 1984. "The Finite Element Method Displayed", John Wiley & Sons, New York.
- Dick, J. B. 1950. "The Fundamentals of Natural Ventilation of Houses", Journal of the Institution of Heating and Ventilating Engineers, London, UK. June.
- Etheridge, D. W. 1977. "Crack Flow Equations and Scale Effect", Building and Environment, Vol. 12, Pergamon Press, Oxford, UK.
- Fanger, P.O. 1970. "Thermal Comfort: Analysis and Applications in Environmental Engineering", McGraw-Hill, New York.
- Gerald, C.F. and P.O. Wheatley. 1989. "Applied Numerical Analysis", 4th Edition, Addison-Wesley Publishing Company, Reading, Massachusetts.
- Hill, D., A. Kirkpatrick, and P. Burns. 1986. "Analysis and Measurements of Interzonal Natural Convection Heat Transfer in Buildings", Journal of Solar Energy Engineering, ASME, Vol. 108, August.
- Isaacs, L. T. and K. G. Mills. 1980. "Linear Theory Methods for Pipe Network Analysis", Journal of the Hydraulics Division, Proceedings of ASCE, Vol. 106, No. HY7, July.
- Jeppson, R. W. 1976. "Analysis of Flow in Pipe Networks", Ann Arbor Science Publishers, Ann Arbor, Michigan.
- Kammerud, R., E. Ceballos, V. Curtis, W. Place, and B. Andersson. 1984. "Ventilation Cooling of Residential Buildings", ASHRAE Transactions, Vol. 90, Part 1.

- Kincaid, D. R. and E. W. Cheney, 1991, "Numerical Analysis : Mathematics of Scientific Computing", Brooks/Cole Publishing Company, Pacific Grove, California.
- Klote, J. H. and J. W. Fothergill, Jr. 1983, "Design of Smoke Control Systems for Buildings", ASHRAE Publications, Atlanta, Georgia. September.
- Levins, W.P. and M. A. Karnitz. 1987. "Cooling Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation", Report No. ORNL/CON-226, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May.
- Liddament, M. W. 1988. "The Calculation of Wind Effect on Ventilation", ASHRAE Transactions, Vol. 94, Part 2.
- McQuiston, F. C. and J. D. Parker. 1988. "Heating, Ventilating and Air Conditioning: Analysis and Design", 3rd Edition, John Wiley & Sons, New York.
- Nemeth, R. J. and L. K. Lawrie. 1991. "Building Comfort Analysis Using BLAST: A Case Study", Report No. TR E-91/12, U.S. Army Construction Engineering Research Laboratory (USACERL), Champaign, Illinois, September.
- Osborne, W. C. 1977. "Fans", 2nd Edition, Pergamon Press, New York. ✓
- Persily, A. K. and R. A. Grot. 1985. "The Airtightness of Office-Building Envelopes", Thermal Performance of the Exterior Envelopes of Buildings III, Proceedings of the ASHRAE/DOE/BTECC Conference in Clearwater Beach, Florida. December.
- Pissanetzky, S. 1984. Sparse Matrix Technology, Academic Press, Orlando, Florida.
- Said, M. N. A. 1988. "A Review of Smoke Control Models", ASHRAE Journal, Vol. 30, No. 4, April.
- Sherman, M. H. and D. T. Grimsrud. 1980. "Infiltration-Pressurization Correlation: Simplified Physical Modeling", ASHRAE Transactions, Vol. 86, Part 2.
- Shaw, C. Y. and L. Jones. 1979. "Air Tightness and Air Infiltration of School Buildings", ASHRAE Transactions, Vol. 85, Part 1.
- Shaw, C. Y. and G. T. Tamura. 1977. "The Calculation of Air Infiltration Rates Caused by Wind and Stack Action for Tall Buildings", ASHRAE Transactions, Vol. 83, Part 2.
- Spitler, J. D. 1990. "An experimental Investigation of Air Flow and Convective Heat Transfer in Enclosures having Large Ventilative Flow Rates", Ph. D. Thesis, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.
- Spitler, J. D., C. O. Pedersen, and D. E. Fisher. 1991. "Interior Convective Heat Transfer in Buildings with Large Ventilative Flow Rates", ASHRAE Transactions, Vol. 97, Part 1.

- Stoecker, W. F. 1989. "Design of Thermal Systems", 3rd Edition, McGraw-Hill, New York.
- Swami, M. V. and S. Chandra. 1988. "Correlations for Pressure Distribution on Buildings and Calculation of Natural-Ventilation Airflow", ASHRAE Transactions, Vol. 94, Part 1.
- Tamura, G. T. 1979. "The Calculation of House Infiltration Rates", ASHRAE Transactions, Vol. 85, Part 1.
- Vickery, B. J., R. E. Baddour, and C. A. Karakatsanis. 1983. "A Study of the External Wind Pressure Distributions and Induced Internal Ventilation Flow in Low-Rise Industrial and Domestic Structures", Report No. BLWT-SS2-1983, Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, Canada. January.
- Walton, G. N. 1982. "Airflow and Multiroom Thermal Analysis", ASHRAE Transactions, Vol. 88, Part 2.
- Walton, G. N. 1984. "A Computer Algorithm for Predicting Infiltration and Interroom Airflows", ASHRAE Transactions, Vol. 90, Part 1.
- Walton, G. N. 1989. "AIRNET - A computer Program for Building Airflow Network Modeling", Report No. NISTIR 89-4072, National Institute of Standards and Technology, Gaithersburg, Maryland. April.
- Weber, D. D. and R. J. Kearney. 1980. "Natural Convective Heat Transfer through an Aperture in Passive Solar Heated Buildings", 5th National Passive Solar Conference, American Solar Energy Society.
- Wiren, B. G. 1985. "Effects of Surrounding Buildings on Wind Pressure Distributions and Ventilation Losses for Single-Family Houses", Report No. M85:19, The National Swedish Institute for Building Research, December.
- Wolfert, C. K. and H. S. Hinrichs. 1974. "Fundamentals of Residential Attic Ventilation", H C Products Co., Princeville, Illinois.
- Wood, D. J. and A. G. Rayes. 1981. "Reliability of Algorithms for Pipe Network Analysis", Journal of the Hydraulics Division, Proceedings of ASCE, Vol. 107, No. HY10, October.

APPENDICES

APPENDIX A

DESCRIPTION OF INPUT DATA FILES

Network Data File

This file contains physical data of nodes, node-to-node linkage data, and data on flow characteristics of elements present in a network. The parameter in the "size.inc" include-file which specifies the array dimension should be equal to at least the total number of links or total number of nodes in the network, whichever is greater. The following is the description of input data required for stand-alone version of the Network model in the order of their appearance in the network data file. Any necessary changes needed in the network data file for BLAST-coupled version are also indicated.

- 1) number of hours of building airflow network simulation

Note: This parameter is not needed in the case of BLAST-coupled version

- 2) total number of nodes in the network
- 3) total number of ambient/constant pressure nodes in the network
- 4) total number of links in the network
- 5) barometric pressure at the location

Note: This parameter is not needed in the case of BLAST-coupled version

- 6) type of flow element number of such elements

- 7) i. If the element type is crack

name init_coef lam_coef turb_coef flow_exp area hy_dia

- ii. If the element type is door

name init_coef lam_coef turb_coef flow_exp door_ht width C_D

iii. If the element type is duct

name init_coef lfl_coef ldl_coef tdl_coef duct_lt hy_dia area rough

iv. If the element type is fan

name fan_pow

8) 'node data' total number of nodes in the network

9) node number node_pres node_ht node_temp

Note: i) The numbering of nodes should be done such that known pressure nodes are always numbered before unknown pressure nodes.

ii) The parameter "node_temp" is not needed in the case of BLAST-coupled version.

10) name node(from) link_ht node(to) link_ht

The following gives the description of abbreviated parameters shown above:

name : name of an airflow element
 init_coef : linear flow initialization coefficient of crack, door, or duct element
 lam_coef : laminar flow coefficient of crack or door element
 turb_coef : turbulent flow coefficient of crack or door element
 flow_exp : flow exponent of crack or door element
 area : area of crack, door, or duct element (m²)
 hy_dia : hydraulic diameter of crack or duct element (m)
 door_ht : height of door element (m)
 width : width of door element (m)
 C_D : discharge coefficient of door element
 duct_lt : duct length (m)
 rough : duct roughness dimension (m)
 lfl_coef : laminar frictional loss coefficient of duct element
 ldl_coef : laminar dynamic loss coefficient of duct element
 tdl_coef : turbulent dynamic loss coefficient of duct element
 fan_pow : fan power (W)
 node_pres : static node pressure at node height in an undisturbed flow without wind and stack effects (Pa)
 node_ht : node height from reference level (m)
 node_temp : node temperature (°C)
 link_ht : link height with respect to node height level (m)

Sample Input Data File for an Airflow Network ("izafnw.dat" file)

```

8670
6
4
7
101325.0
'crack' 2
'crk1' 2.2769e-7 2.2769e-7 0.000848528 0.5 0.001 0.03162
'crk2' 7.2e-6 7.2e-6 0.00848528 0.5 0.01 0.1
'door' 1
'door1' 0.015575 0.015575 1.764945 0.5 2.0 0.8 0.78
'duct' 2
'duct1' 128.0 64.0 0.0 0.0 2.0 0.25 0.04909 0.00015
'duct2' 128.0 64.0 0.0 0.0 3.0 0.25 0.04909 0.00015
'fan' 1
'fan1' 745.7
'node data' 6
1 0.00 0.00 20.00
2 0.00 0.00 20.00
3 0.00 0.00 20.00
4 0.00 0.00 20.00
5 0.00 0.50 24.00
6 0.00 0.50 24.00
'door1' 1 0.50 5 0.00
'crk2' 1 1.50 6 1.00
'duct2' 2 4.00 6 3.50
'crk1' 3 1.50 6 1.00
'crk1' 4 0.50 5 0.00
'duct1' 5 3.50 6 3.50
'fan1' 5 3.50 3 4.00

```

Surface Pressure Coefficient Data File

This data file contains surface pressure coefficients of building surfaces exposed to ambient conditions such that it depicts site obstruction features at any particular wind direction. Wind angles are measured with respect to the North direction. Pressure coefficients can be positive or negative depending on windward or leeward exposure of a building surface.

Typically for each building surface there are sixteen pressure coefficient values in this data file (i.e., at each $22\frac{1}{2}^{\circ}$ interval in wind angle from 0° to 360°). For any other intermediate wind angle, the pressure coefficient can be computed using suitable interpolation techniques. However, if user wants to build his own input data file with fewer or more coefficients using any other pressure coefficient database, the following guidelines

are recommended: 1) number of pressure coefficients should be the same for all building surfaces. 2) increment in wind angle (ranging from 0° to 360°) should be the same between each consecutive coefficients in the data file. 3) information about this total number of pressure coefficient values for each building surface should go into "size.inc" include file as a parameter as shown below before compiling the source code.

```
parameter (imax = 20, ncp = 16)
```

where "imax" is the array dimensioning parameter and "ncp" corresponds to the total number of pressure coefficients for each building surface in "izafcp.dat" input data file.

Sample Surface Pressure Coefficient Data File ("izafcp.dat" file)

The following is a sample surface pressure coefficient data file for a simple rectangular building. The four lines of data correspond to north, east, south, and west walls of the building respectively.

```
.600 .5543 .4243 .2296 .000 -.2296 -.4243 -.5543 -.600 -.5543 -.4243 -.2296 .000 .2296 .4243 .5543
.000 .2296 .4243 .5543 .600 .5543 .4243 .2296 .000 -.2296 -.4243 -.5543 -.600 -.5543 -.4243 .2296
-.600 -.5543 -.4243 -.2296 .000 .2296 .4243 .5543 .600 .5543 .4243 .2296 .000 -.2296 -.4243 -.5543
.000 -.2296 -.4243 -.5543 -.600 -.5543 -.4243 -.2296 .000 .2296 .4243 .5543 .600 .5543 .4243 .2296
```

Weather Data File

Hourly wind speed (m/s) and wind angles (in degrees measured with respect to the north direction) are listed in this data file (i.e., "izafweth.dat" file) as follows:

```
wind speed    wind angle
```

However in the case of the BLAST-coupled version of the Network model, this input file is not necessary.

APPENDIX B

INPUT DATA FILES FOR ELEMENT
AIRFLOW VALIDATION TESTS

Data File for Crack Airflow Validation Tests

```
1
4
2
3
101325.0
'crack' 5
'crk1' 7.2e-9 7.2e-9 0.000848528 0.5 0.0001 0.01
'crk2' 2.2769e-7 2.2769e-7 0.000848528 0.5 0.001 0.03162
'crk3' 7.2e-6 7.2e-6 0.00848528 0.5 0.01 0.1
'crk4' 2.2769e-4 2.2769e-4 0.0848528 0.5 0.1 0.3162
'crk5' 7.2e-3 7.2e-3 0.848528 0.5 1.0 1.0
'node data' 5
1 50.00 0.00 20.00
2 -50.00 0.00 20.00
3 0.00 0.00 20.00
4 0.00 0.00 20.00
'crk1' 1 0.00 3 0.00
'crk1' 3 0.00 4 0.00
'crk1' 4 0.00 2 0.00
```

Data File for Doorway Airflow Validation Tests

```
1
2
1
1
101325.0
'door' 1
'door1' 0.015575 0.015575 1.764945 0.5 2.0 0.8 0.78
'node data' 2
1 0.00 0.00 18.00
2 0.00 0.00 22.00
'door1' 1 0.00 2 0.00
```

Data File for Equivalent Multiple Opening Model for Doorway

```

1
2
1
10
101325.0
'crack' 1
'crk1' 0.000623 0.000623 0.176494 0.5 0.16 0.32
'node data' 2
1 0.00 0.00 18.00
2 0.00 0.00 22.00
'crk1' 1 0.1 2 0.1
'crk1' 1 0.3 2 0.3
'crk1' 1 0.5 2 0.5
'crk1' 1 0.7 2 0.7
'crk1' 1 0.9 2 0.9
'crk1' 1 1.1 2 1.1
'crk1' 1 1.3 2 1.3
'crk1' 1 1.5 2 1.5
'crk1' 1 1.7 2 1.7
'crk1' 1 1.9 2 1.9

```

Data Files for Duct Airflow Validation Tests

Data File for Validation Test #1

```

1
4
2
3
101325.0
'duct' 3
'duct1' 128.0 64.0 0.0 0.0 2.0 0.25 0.04909 0.00015
'duct2' 128.0 64.0 0.0 0.0 3.0 0.25 0.04909 0.00015
'duct3' 128.0 64.0 0.0 0.0 5.0 0.25 0.04909 0.00015
'node data' 4
1 9.00 0.00 20.00
2 0.00 0.00 20.00
3 0.00 0.00 20.00
4 0.00 0.00 20.00
'duct1' 1 0.00 3 0.00
'duct2' 3 0.00 4 0.00
'duct3' 4 0.00 2 0.00

```

Data File for Validation Test #2

```

1
10
3
9
101325.0
'duct' 8
'duct1' 128.0 64.0 0.00 0.00 2.0 0.20 0.03142 0.00015
'duct2' 128.0 64.0 0.00 0.00 3.0 0.15 0.01767 0.00015
'duct3' 128.0 64.0 0.00 0.00 5.0 0.30 0.07069 0.00015
'duct4' 128.0 0.0 3.34 3.34 0.0 0.20 0.03142 0.00015
'duct5' 128.0 0.0 2.63 2.63 0.0 0.15 0.01767 0.00015
'duct6' 128.0 0.0 0.09 0.09 0.0 0.20 0.03142 0.00015
'duct7' 128.0 0.0 0.51 0.51 0.0 0.15 0.01767 0.00015
'duct8' 128.0 0.0 0.22 0.22 0.0 0.20 0.03142 0.00015
'node data' 10

```

```

1  50.00  0.00  20.00
2  0.00  0.00  20.00
3  0.00  0.00  20.00
4  0.00  0.00  20.00
5  0.00  0.00  20.00
6  0.00  0.00  20.00
7  0.00  0.00  20.00
8  0.00  0.00  20.00
9  0.00  0.00  20.00
10 0.00  0.00  20.00
'duct3' 1  0.00  4  0.00
'duct6' 4  0.00  5  0.00
'duct1' 5  0.00  6  0.00
'duct8' 6  0.00  7  0.00
'duct1' 7  0.00  8  0.00
'duct4' 8  0.00  3  0.00
'duct7' 4  0.00  9  0.00
'duct2' 9  0.00 10  0.00
'duct5' 10 0.00  2  0.00

```

Data File for Fan Airflow Validation Tests

```

1
4
2
3
101325.0
'duct' 2
'duct1' 128.0  64.0  0.0  0.0  0.5  0.25  0.04909  0.00015
'duct2' 128.0  64.0  0.0  0.0  5.0  0.20  0.03142  0.00015
'fan' 1
'fan1' 745.7
'node data' 4
1  0.00  0.00  20.00
2  0.00  0.00  20.00
3  0.00  0.00  20.00
4  0.00  0.00  20.00
'duct1' 1  0.00  3  0.00
'fan1' 3  0.00  4  0.00
'duct2' 4  0.00  2  0.00

```

Data File for Stack Pressure Validation Tests

```

1
2
1
2
101325.0
'crack' 1
'crk1' 9.0e-7  9.0e-7  0.00212132  0.5  0.0025  0.05
'node data' 2
1  0.00  0.00  35.00
2  0.00  0.00  20.00
'crk1' 1  0.00  2  0.00
'crk1' 1  5.00  2  5.00

```

Data File for Wind Pressure Validation Tests

```
1
3
2
2
101325.0
'crack' 1
'crk1' 7.2e-6 7.2e-6 0.00848528 0.5 0.01 0.1
'node data' 3
1 0.00 0.00 20.00
2 0.00 0.00 20.00
3 0.00 0.00 20.00
'crk1' 1 0.00 3 0.00
'crk1' 3 0.00 2 0.00
```


APPENDIX C

DESCRIPTION OF AIRFLOW NETWORKS USED IN COMPUTATION TIME TESTS

The following networks (Figures C.1, C.2 and C.3) were used in studying the computation time requirements of the Network model using different correction techniques in Newton's method. The numbers near the openings in Figures C.1 and C.2 represent the areas of the openings in square meters. In Figure C.3, the numbers indicate the lengths and diameters of the connecting ducts in meters. And the fan powers are indicated in kilo-watts.

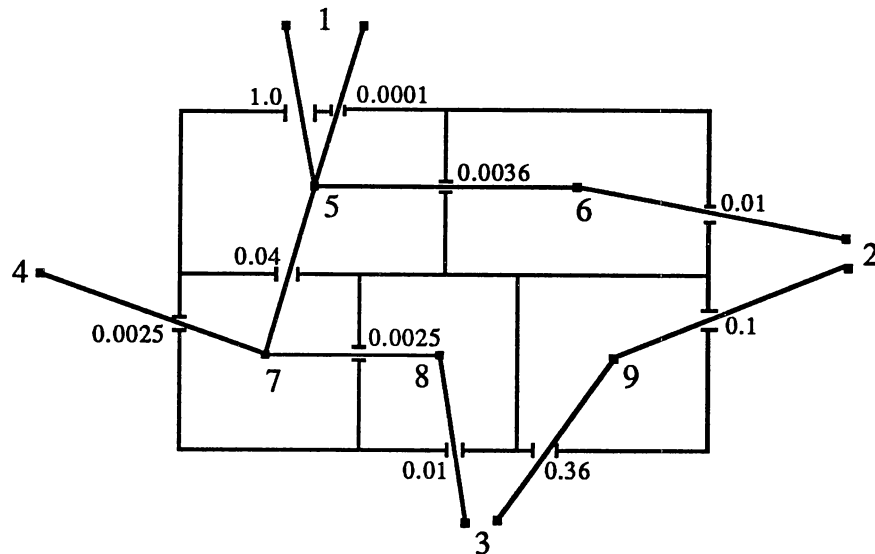


Figure C.1 Network #1 for Computation Time Tests

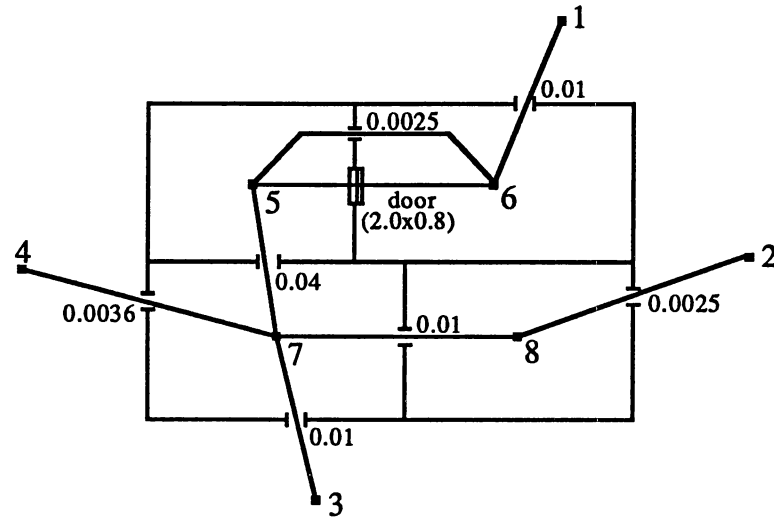


Figure C.2 Network #2 for Computation Time Tests

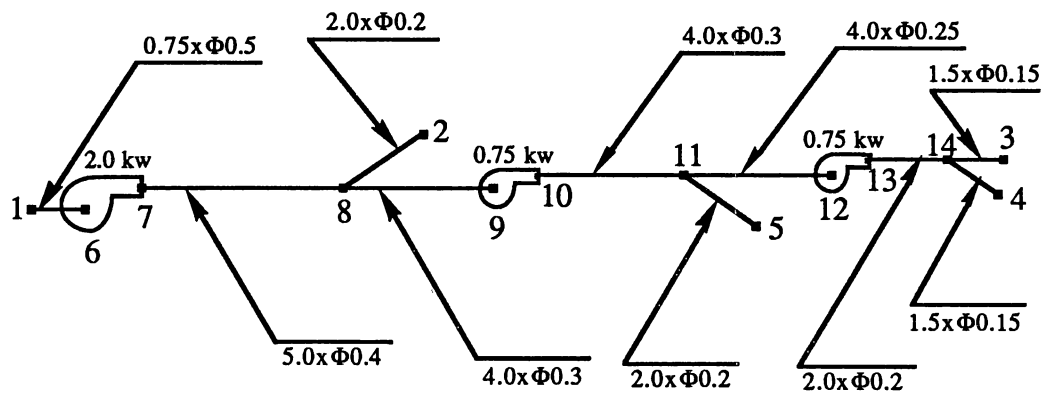


Figure C.3 Network #3 for Computation Time Tests

APPENDIX D

ATTIC VENTILATION AND THERMAL COMFORT
TEST HOUSE DETAILS

Test House Sketch

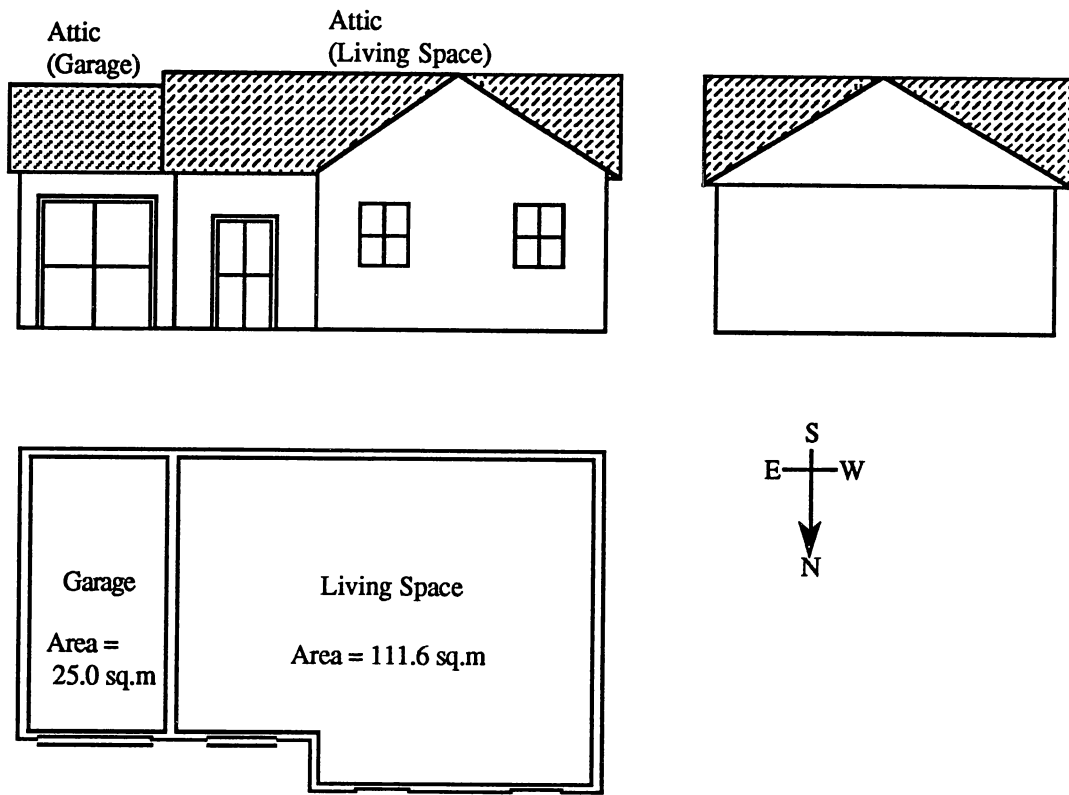


Figure D.1 Floor Plan, Elevation and Side View of the Test House

Typical Sketches of the Attic Ventilation Schemes Studied

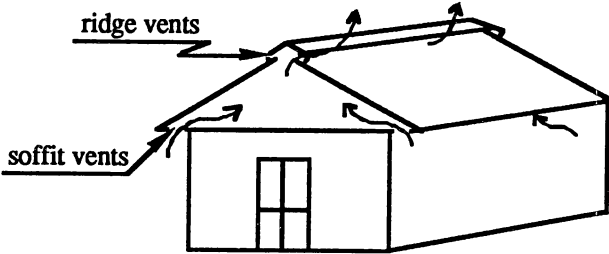


Figure D.2 Ridge-Soffit Ventilation

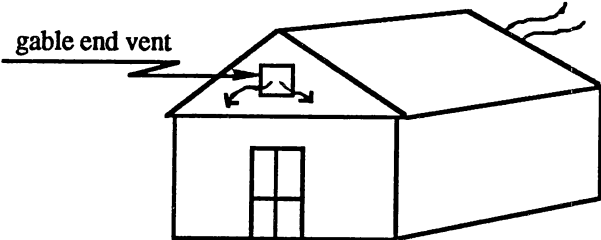


Figure D.3 Gable End Ventilation

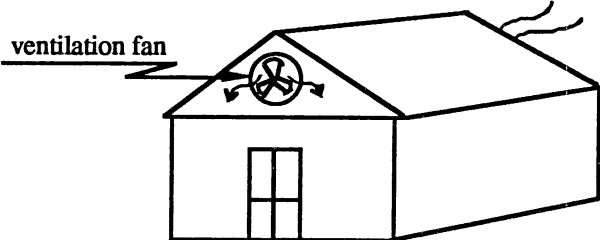


Figure D.4 Powered Ventilation

TABLE VIII
INSIDE DIMENSIONS OF THE TEST HOUSE

| Zone | Area (m ²) | Volume (m ³) |
|--------------------|------------------------|--------------------------|
| Living Space | 111.60 | 281.70 |
| Garage | 25.00 | 68.40 |
| Attic-Living Space | 111.60 | 81.50 |
| Attic-Garage | 25.00 | 9.20 |
| Crawl Space | 111.60 | 106.70 |

TABLE IX
DETAILS OF VENTILATION SCHEMES

| | |
|--------------------------|---|
| Ridge-Soffit Ventilation | Four continuous ridge vents each of 0.06 m width, two of which are 12.00 m long and the other two are of 9.0 m long. Twelve soffit vents of 0.04 m ² inlet area (6 on each roof overhang). |
| Gable-End Ventilation | Four square openings of 0.36 m ² area (one on each direction). |
| Powered Ventilation | Constant power fan of 2.0 hp coupled with two ventilation inlets each of 0.36 m ² area. |

Sample BLAST Input File

```

BEGIN INPUT;
  RUN CONTROL:
    NEW ZONES,
    REPORTS(FANGER),
    REPORTS(ZONE LOADS),
    UNITS(IN=ENGLISH, OUT=METRIC);
  TEMPORARY LOCATION:
    COLUMBIA MISSOURI
    = (LAT=38.97, LONG=92.37, TZ=6.0);
  END;
  TEMPORARY DESIGN DAYS:
    COLUMBIA SUMMER
    = (HIGH=94.0, LOW=71.0, WB=74.0, DATE=21JUL, PRES=396.0,
      WS=683.4, DIR=237.0, CLEARNESS=0.97, WEEKDAY);
    COLUMBIA WINTER
    = (HIGH=24.0, LOW=4.0, WB=23.0, DATE=21JAN, PRES=397.00,
      WS=921.0, DIR=282.0, CLEARNESS=0.97, WEEKDAY);
  END;
  TEMPORARY MATERIALS:
    IN150
    = (R=9.534, ABS=0.75, TABS=0.90, ROUGH);
    IN151
    = (R=9.977, ABS=0.75, TABS=0.90, ROUGH);
    IN152
    = (R=18.330, ABS=0.75, TABS=0.90, ROUGH);
    B50
    = (L=0.0167, K=0.0700, D=37.0, CP=0.600, ABS=0.78,
      TABS=0.90, MEDIUM SMOOTH);
    E10
    = (L=0.0417, K=0.4200, D=100.0, CP=0.200, ABS=0.92,
      TABS=0.90, SMOOTH);
    BM5
    = (L=0.0005, K=137.00, D=168.7, CP=0.215, ABS=0.50,
      TABS=0.97, VERY SMOOTH);
    WD50
    = (L=0.0313, K=0.0920, D=45.0, CP=0.300, ABS=0.78,
      TABS=0.90, MEDIUM SMOOTH);
  END;
  TEMPORARY WALLS:
    XW150
    = (WD50 ,
      BM1 ,
      BB7 ,
      IN150 ,
      E10);
    BSWALL
    = (C13);
    PT50
    = (E10 ,
      IN151 ,
      E10);
    PT51
    = (E10 ,
      B50 ,
      E10);
  END;
  TEMPORARY ROOFS:
    RF50
    = (RF3 ,
      BM1 ,
      BB7);
    RF51
    = (BM5 ,
      AR2 ,
      BM5 ,
      IN151 ,
      E10);
    RF53

```

```

    = (BB37 ,
      BM1 ,
      BB7 ,
      IN152);
RF52
  = (B50 ,
    E10);
END;
TEMPORARY FLOORS:
FL102
  = (E10 ,
    IN151 ,
    BM5 ,
    AR2 ,
    BM5);
FL103
  = (DIRT 12 IN);
FL100
  = (IN152 ,
    BB7 ,
    BM1 ,
    BB37);
FL101
  = (E10 ,
    B50);
END;
TEMPORARY DOORS:
SWD1
  = (B7);
END;
TEMPORARY CONTROLS (LIVING SPACE):
PROFILES:
  HTCOOL=(1.0000 AT 64.00, 0.0000 AT 65.00);
SCHEDULES:
  MONDAY THRU FRIDAY=(0 TO 24-HTCOOL),
  SATURDAY=(0 TO 24-HTCOOL),
  SUNDAY=(0 TO 24-HTCOOL),
  HOLIDAY=(0 TO 24-HTCOOL),
  SPECIAL1=(0 TO 24-HTCOOL),
  SPECIAL2=(0 TO 24-HTCOOL),
  SPECIAL3=(0 TO 24-HTCOOL),
  SPECIAL4=(0 TO 24-HTCOOL);
END;
PROJECT="THERMAL COMFORT TESTS";
LOCATION=COLUMBIA MISSOURI;
DESIGN DAYS=COLUMBIA SUMMER;
WEATHER TAPE FROM 01 JAN THRU 31 DEC;
GROUND TEMPERATURES=(65, 65, 65, 65, 65, 65, 65, 65, 65, 65, 65, 65);
BEGIN BUILDING DESCRIPTION;
  BUILDING="IZAF TEST HOUSE";
  NORTH AXIS=0.00;
  SOLAR DISTRIBUTION=0;
  ZONE 1 "LIVING SPACE ":
    ORIGIN:(0.00, 0.00, 0.00);
    NORTH AXIS=0.00;
  EXTERIOR WALLS :
    STARTING AT(0.00, 29.50, 0.00)
    FACING(270.00)
    TILTED(90.00)
    XW150 (29.50 BY 7.92),
    STARTING AT(23.70, 29.50, 0.00)
    FACING(0.00)
    TILTED(90.00)
    XW150 (23.70 BY 7.92)
    WITH WINDOWS OF TYPE
      DPW (3.00 BY 4.75)
      REVEAL(0.00)
      AT (8.00, 1.70)
    WITH WINDOWS OF TYPE
      DPW (3.00 BY 4.75)
      REVEAL(0.00)
      AT (16.00, 1.70),

```

STARTING AT(23.70, 26.00, 0.00)
 FACING(90.00)
 TILTED(90.00)
 XW150 (3.50 BY 7.92),
 STARTING AT(43.00, 26.00, 0.00)
 FACING(0.00)
 TILTED(90.00)
 XW150 (19.30 BY 7.92)
 WITH WINDOWS OF TYPE
 DPW (6.42 BY 4.75)
 REVEAL(0.00)
 AT (4.50, 1.70)
 WITH DOORS OF TYPE
 SWD (3.00 BY 6.60)
 AT (15.00, 0.00)
 WITH OVERHANG (19.30 BY 3.50)
 AT (0.00, 7.92),
 STARTING AT(0.00, 0.00, 0.00)
 FACING(180.00)
 TILTED(90.00)
 XW150 (43.00 BY 7.92)
 WITH WINDOWS OF TYPE
 DPW (2.75 BY 5.83)
 REVEAL(0.00)
 AT (7.00, 0.80)
 WITH DOORS OF TYPE
 GLD (5.75 BY 6.25)
 AT (35.00, 0.00);
 INTERZONE PARTITIONS :
 STARTING AT(43.00, 0.00, 0.00)
 FACING(90.00)
 TILTED(90.00)
 PT50 (26.00 BY 7.92)
 ADJACENT TO ZONE (2);
 INTERZONE FLOORS :
 STARTING AT(0.00, 29.50, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL100 (23.70 BY 29.50)
 ADJACENT TO ZONE (5),
 STARTING AT(23.70, 26.00, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL100 (19.30 BY 26.00)
 ADJACENT TO ZONE (5);
 INTERZONE CEILINGS :
 STARTING AT(0.00, 0.00, 7.92)
 FACING(180.00)
 TILTED(0.00)
 RF51 (23.70 BY 29.50)
 ADJACENT TO ZONE (3),
 STARTING AT(23.70, 0.00, 7.92)
 FACING(180.00)
 TILTED(0.00)
 RF51 (19.30 BY 26.00)
 ADJACENT TO ZONE (3);
 INTERNAL MASS: PT51
 (219.30 BY 10.00);
 PEOPLE=5, FROM 01 JAN THRU 31 DEC;
 RELATIVE HUMIDITY=0.4, CONSTANT;
 METABOLIC RATE=1.0, CONSTANT;
 CLOTHING INSULATION=0.5, CONSTANT;
 CONTROLS=LIVING SPACE ,
 3412000.0 HEATING,
 0.00 PERCENT MRT,
 FROM 01 JAN THRU 31 DEC;
 END ZONE;
 ZONE 2 "GARAGE ":
 ORIGIN:(43.00, 0.00, 0.00);
 NORTH AXIS=0.00;
 EXTERIOR WALLS :
 STARTING AT(11.60, 23.20, 0.00)

FACING(0.00)
 TILTED(90.00)
 XW150 (11.60 BY 8.25)
 WITH DOORS OF TYPE
 SWD1 (9.00 BY 7.25)
 AT (1.30, 0.00),
 STARTING AT(11.60, 0.00, 0.00)
 FACING(90.00)
 TILTED(90.00)
 XW150 (23.20 BY 8.25),
 STARTING AT(0.00, 0.00, 0.00)
 FACING(180.00)
 TILTED(90.00)
 XW150 (11.60 BY 8.25);
 INTERZONE PARTITIONS :
 STARTING AT(0.00, 23.20, 0.00)
 FACING(270.00)
 TILTED(90.00)
 PT50 (26.00 BY 7.92)
 ADJACENT TO ZONE (1);
 SLAB ON GRADE FLOORS :
 STARTING AT(0.00, 23.20, 0.00)
 FACING(180.00)
 TILTED(180.00)
 SLAB FLOOR (11.60 BY 23.20);
 INTERZONE CEILINGS :
 STARTING AT(0.00, 0.00, 8.25)
 FACING(180.00)
 TILTED(0.00)
 RF52 (11.60 BY 23.20)
 ADJACENT TO ZONE (4);
 END ZONE;
 ZONE 3 "ATTIC - LIVING SPACE ":
 ORIGIN:(0.00, 0.00, 7.92);
 NORTH AXIS=0.00;
 EXTERIOR WALLS :
 STARTING AT(0.00, 29.50, 0.00)
 XW150 ((29.5,0),(14.75,6.15))
 FACING(270.00)
 TILTED(90.00),
 STARTING AT(23.70, 29.50, 0.00)
 XW150 ((23.7,0),(11.85,5.50))
 FACING(0.00)
 TILTED(90.00);
 INTERZONE FLOORS :
 STARTING AT(0.00, 29.50, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL102 (23.70 BY 29.50)
 ADJACENT TO ZONE (1),
 STARTING AT(23.70, 26.00, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL102 (19.30 BY 26.00)
 ADJACENT TO ZONE (1);
 ROOFS :
 STARTING AT(43.00, 29.50, 0.00)
 FACING(0.00)
 TILTED(22.60)
 RF50 (19.30 BY 15.98),
 STARTING AT(23.70, 29.50, 0.00)
 RF50 ((11.85,14.31),(11.85,15.98),(0,15.98))
 FACING(0.00)
 TILTED(22.60),
 STARTING AT(0.00, 29.50, 0.00)
 RF50 ((0,15.98),(-11.85,15.98),(-11.85,14.31))
 FACING(0.00)
 TILTED(22.60),
 STARTING AT(0.00, 0.00, 0.00)
 FACING(180.00)
 TILTED(22.60)
 RF50 (43.00 BY 15.98),

STARTING AT(0.00, 29.50, 0.00)
 RF50 ((13.21,0),(0,13.05))
 FACING(270.00)
 TILTED(24.80),
 STARTING AT(23.70, 29.50, 0.00)
 RF50 ((0,13.05),(-13.21,13.05))
 FACING(90.00)
 TILTED(24.80);
 END ZONE;
 ZONE 4 "ATTIC - GARAGE ":
 ORIGIN:(43.00, 0.00, 8.25);
 NORTH AXIS=0.00;
 EXTERIOR WALLS :
 STARTING AT(11.60, 0.00, 0.00)
 XW150 ((23.2,0),(11.6,4.83))
 FACING(90.00)
 TILTED(90.00);
 INTERZONE FLOORS :
 STARTING AT(0.00, 23.20, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL101 (11.60 BY 23.20)
 ADJACENT TO ZONE (2);
 ROOFS :
 STARTING AT(11.60, 23.20, 0.00)
 FACING(0.00)
 TILTED(22.60)
 RF50 (11.60 BY 12.60),
 STARTING AT(0.00, 0.00, 0.00)
 FACING(180.00)
 TILTED(22.60)
 RF50 (11.60 BY 12.60);
 END ZONE;
 ZONE 5 "CRAWL SPACE ":
 ORIGIN:(0.00, 0.00, -3.00);
 NORTH AXIS=0.00;
 BASEMENT WALLS :
 STARTING AT(0.00, 29.50, 0.00)
 FACING(270.00)
 TILTED(90.00)
 BSWALL (29.50 BY 3.00),
 STARTING AT(23.70, 29.50, 0.00)
 FACING(0.00)
 TILTED(90.00)
 BSWALL (23.70 BY 3.00),
 STARTING AT(23.70, 26.00, 0.00)
 FACING(90.00)
 TILTED(90.00)
 BSWALL (3.50 BY 3.00),
 STARTING AT(43.00, 26.00, 0.00)
 FACING(0.00)
 TILTED(90.00)
 BSWALL (19.30 BY 3.00),
 STARTING AT(43.00, 0.00, 0.00)
 FACING(90.00)
 TILTED(90.00)
 BSWALL (26.00 BY 3.00),
 STARTING AT(0.00, 0.00, 0.00)
 FACING(180.00)
 TILTED(90.00)
 BSWALL (43.00 BY 3.00);
 FLOORS :
 STARTING AT(0.00, 29.50, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL103 (23.70 BY 29.50),
 STARTING AT(23.70, 26.00, 0.00)
 FACING(180.00)
 TILTED(180.00)
 FL103 (19.30 BY 26.00);
 INTERZONE CEILINGS :
 STARTING AT(0.00, 0.00, 3.00)

FACING(180.00)
TILTED(0.00)
RF53 (23.70 BY 29.50)
ADJACENT TO ZONE (1),
STARTING AT(23.70, 0.00, 3.00)
FACING(180.00)
TILTED(0.00)
RF53 (19.30 BY 26.00)
ADJACENT TO ZONE (1);
END ZONE;
END BUILDING DESCRIPTION;
END INPUT;

VITA

SUNILSEN PERAMANU

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