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Computer Simulation of Natural Ventilation Airflow

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APPLIED SCIENCE DIVISION

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Computer Simulation of Natural Ventilation Airflow

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ABSTRACT

This paper describes the current limitations, as well as recent improvements, in the capability of computer simulation programs to model natural ventilation airflow through buildings. The advantages and limitations of two techniques -- the mass balance approach and the finite domain approach -- are discussed. Results are shown from two sets of simulations, using typical building configurations, to illustrate the usefulness of each technique in predicting wind induced ventilation rate.

INTRODUCTION

Buildings that are properly designed for natural ventilation cooling can significantly reduce or eliminate the need for mechanical air conditioning, while maintaining or improving the level of comfort of the building occupants. However, the physical processes of heat and mass transfer and human comfort are very complex, and all are not yet fully understood. Hence, a comprehensive computer program does not yet exist to model all the processes necessary to predict the performance of a naturally ventilated building.

The airflow rate through a building is a fundamental concern because of its impact on the level of comfort of the building occupants and the resulting cooling energy consumption (Byrne et al. 1986). The natural ventilation flow rate is driven by a difference in pressure across the building envelope, which is effected by the location and size of nearby obstructions (e.g., other buildings, trees, etc.) as well as terrain density (e.g., urban, rural, etc.) and regional geographic features (e.g., lakes, mountains, etc.). This paper deals with the prediction of interior airflow when the air pressures are known on the outside surfaces of the building. Two techniques are described to simulate airflow -- the mass balance approach and the finite domain approach. Each approach has advantages and limitations which are discussed in the context of example problems.

WIND FLOW AROUND BUILDINGS

The airflow field around a building, including the air velocity and building surface pressure, is significantly affected by the location, size and shape of nearby obstructions (such as other buildings or groups of trees), as well as the size and shape of the building itself. An understanding of this flow field is necessary for the accurate prediction of natural ventilation airflow through buildings and is also useful for analyzing human comfort on the street level and wind loading on the structure of buildings.

For the purpose of calculating natural ventilation airflow rates, the exterior flow field is frequently characterized by pressure coefficients for selected points on the surface of a building. A pressure coefficient is defined as the ratio of the dynamic wind pressure at a given point on a building's surface to the dynamic wind pressure in the free stream at a reference height. This coefficient, along with the wind speed, direction and air density (normally obtained from a weather tape), is used to determine the actual surface pressure for each time step in a simulation. Pressure coefficients are normally recorded at several points (frequently 20 or more) on each building surface that has ventilation openings, for several wind directions (usually between 8 and 36), resulting in a large database to describe any given building design.

Pressure coefficients can be determined from experimental measurements in a wind tunnel, estimated from regression analysis of previous experiments, or calculated from the basic laws of fluid dynamics. Wind tunnel experimentation has been used extensively in the past to model airflow around buildings (Cermak 1976, Aynsley 1977). However, it is both difficult and expensive to perform a rigorous set of wind tunnel experiments for every building design because each change in the size or shape of the building or surrounding obstructions will alter the magnitude and distribution of the surface pressure. Although wind tunnel experimentation remains the choice where precision is necessary, there has been increasing interest in alternate methods of predicting pressure coefficients.

One approach is to reduce large sets of pressure coefficients to simple equations by regression analysis of previous experimental data (Lee et al. 1980, Allen 1984, Swami and Chandra 1987). In order to reduce the complexity of the problem, these studies have made several simplifying assumptions. For example, Swami and Chandra averaged the measured data, resulting in a constant pressure across the entire area of each surface. Also, the effects of specific design changes (e.g., the addition of wingwalls, overhangs, etc.) and surrounding buildings are not always explicitly included in the regression models. While the effect of these simplifications depends on the specific problem, in general, estimated pressure coefficients are useful only for predicting average ventilation rates and are not sufficiently accurate for a sensitivity study of ventilation design strategies.

There has been considerable recent interest in the use of computer models based on the fundamentals of fluid dynamics to predict wind flow around buildings as well as surface pressure coefficients (Ohisi 1983, Haggkvist et al. 1985, Hanson et al. 1986). Using the conservation equations for fluid flow and empirically derived formulas for certain effects, these models have the potential to supplement or replace wind tunnel experimentation. However, the interaction of large and small scale effects remains difficult to quantify and the numerical solution techniques require significant computer resources. Although a substantial development and validation effort remains, this approach may eventually enable designers to easily and inexpensively compare many different ventilation design strategies. A similar approach (discussed below) has been used for the prediction of air movement within buildings.

AIRFLOW THROUGH BUILDINGS

Natural ventilation airflow through buildings is driven by a difference in pressure across openings in the building envelope and between rooms within the building. This pressure difference is caused by a difference in temperature (the stack effect) as well as the force of the wind. The stack effect can dominate airflow in tall buildings when there is little or no wind, but as the wind speed increases (and nearly always in low rise buildings), the stack effect is less important and ventilation is primarily induced by wind pressure.

Three calculation techniques exist for determining natural ventilation airflow rates in buildings:

1. Simplified models based on a regression of measured airflow rates in typical, usually single zone, buildings.
2. A mass balance of the airflow into and out of each of one or more interconnected zones.
3. A numerical solution of the conservation law equations, possibly combined with empirical relationships for certain effects, using a finite domain method or other numerical scheme.

Simplified models (for example, Sherman and Grimsrud 1980, or Warren and Webb 1980), like regression models used to predict surface pressure coefficients, are primarily useful for estimating typical airflow rates rather than an analysis of ventilation design strategies. Therefore, the discussion here will focus on the mass balance and finite domain solution techniques.

The Mass Balance Approach

The mass balance approach represents a building as a network of nodes (i.e., internal spaces or points on the external building envelope) with connections or openings (i.e., windows, doors, etc.) between the nodes. With this approach, it is possible to solve for the airflow rate through each opening when given the following information:

1. The air temperature of each node, usually obtained from a weather tape for external nodes and from a heat transfer simulation or direct input for internal nodes.
2. The wind pressure of each external node, obtained from surface pressure coefficients along with wind speed, direction and air density from a weather tape.
3. The resistance to airflow of each opening, obtained from empirical relationships.

The airflow through an opening is a function of the size and shape of the opening as well as the pressure difference across it. Empirical relationships have been developed for airflow through several types of openings; a summary is given in ASHRAE (1985). Cockcroft (1979) has accounted for airflow in both directions through a single opening caused by a difference in temperature between the spaces.

In a network of interconnected spaces, the airflow is solved by balancing the mass flow rate into and out of each space. An iterative solution, which is required because the pressure in each space is initially unknown and the flow equations are nonlinear, proceeds until the predicted airflow is within some acceptable tolerance. The solution for an entire network of spaces can be numerically unstable if there are both large and small openings in the network, or if small changes in pressure produce large changes in the airflow rates. Various solution algorithms for this type of problem have been proposed by Cockroft (1979), Walton (1982), Vickery et al. (1983), and Lindberg (1985).

To illustrate the usefulness of the mass balance approach, we analyzed natural ventilation in a typical apartment (Figure 1) at two locations in New Caledonia (latitude 22 S, longitude 166 E). The two sites, Noumea and Poindimie, are on opposite sides of a range of mountains extending the length of the island. We used ESPAIR (Clarke 1985) to simulate the natural ventilation airflow rate, based on measured weather data from January 1984, a month in the middle of the summer in the southern hemisphere. We corrected the measured wind speed to account for differences in terrain between the weather stations (located outside urban areas) and the building sites (assumed to be in low density urban surroundings) using an algorithm described by Sherman and Grimsrud (1982). The surface pressure coefficients are taken from a series of wind tunnel experiments by Vickery et al. (1983) for a low rise building on a suburban site. For the purpose of simulation, we divided the apartment into five airflow zones: living room, kitchen, hall and two bedrooms.

Shown in Figures 2 and 3, is the simulated airflow rate through the apartment living room for each hour during the month of January. We limited the ventilation rate to a maximum of 40 air changes per hour (AC/h) because greater airflow in the floor plan shown might cause occupant discomfort. The ventilation rate shown in Figure 2 for Noumea frequently reaches the maximum and falls below 10 AC/h for only brief periods. For the same period of time, the same apartment in Poindimie (Figure 3) has much less ventilation, with frequent and extended periods below 10 AC/h. In both cases, the ventilation rate is highly irregular due to rapidly fluctuating wind speed and direction. This analysis shows the effect on ventilation of differences in wind direction and speed between two nearby sites that otherwise have similar climates. An architect could use this type of analysis to conclude that the proposed design is acceptable for Noumea, but should be modified, perhaps by changing the orientation, window sizes, or interior partitions, if it to be used in Poindimie. Using this approach, a designer can quickly evaluate various design strategies, with subsequent analysis necessary to account for occupant comfort and the resulting energy consumption.

Although the mass balance approach is widely used to predict air movement in buildings, it has several disadvantages. Inherent to this approach is the assumption of perfect mixing of the air in each space; that is, the air temperature, speed and pressure are constant throughout each space in the network. This assumption can be inaccurate for large spaces, especially if divided with partitions.

With the mass balance approach, it is possible to estimate the air speed only near openings between spaces. Because adequate air movement is an important means of maintaining human comfort in hot climates, this limitation makes it difficult to evaluate the effect of a given design strategy on the level of comfort of the building occupants.

The effects of air momentum are also not accounted for in the mass balance approach. It is therefore impossible to accurately predict the amount of air that enters and then leaves a room without interacting with the balance of the room air, as might happen in a small or narrow room with openings on opposite sides. This limitation makes it difficult to accurately calculate the room energy balance and determine the resulting cooling load and space temperature. However, although the mass balance approach has many limitations, the accuracy of this approach is often acceptable and consistent with the level of uncertainty of other assumptions that are necessary in a comprehensive building energy simulation.

The Finite Domain Approach

In the mass balance approach, the only parameter of interest is the input and output of mass from each zone. That is, no attention is given to what may happen to the air inside each zone, such as short-circuiting, stratification, perfect mixing, stagnant polluted air, water vapor concentration, or the range of air velocity. However, these variables are necessary to characterize the level of comfort in a room, the efficiency of the HVAC system and potential building problems, such as moisture condensation (Fleury 1986). If these parameters need to be quantified, the finite domain method is a more appropriate analytical tool. The comments made here also apply to the finite difference and finite element approaches which employ similar numerical solution techniques. Spectral methods will not be discussed here because of their present limitations at high Rayleigh numbers (Haldenwang et al. 1986).

The finite domain approach represents each thermal zone in a building as a finite number of control volumes or domains. The value of each variable (pressure, temperature, velocity, etc.) is assumed to be constant throughout an entire control volume. The number of control volumes used to represent each thermal zone depends on the problem to be studied and the level of required accuracy. For example, if a designer is interested in local convective heat exchange, attention has to be concentrated near the wall where the boundary layer develops, leading to a very fine grid near each surface because the thermal boundary layer is only a few millimeters deep. Likewise, the core, or central, control volume may be relatively large if it is thermally inactive. The choice of the size of each control volume is, therefore, the result of a detailed analysis of the physical processes to be modeled. The finite domain approach allows for the simultaneous solution of a combination of large and small control volumes.

According to the problem to be solved (dynamic, thermal, two-phase, conjugated, etc.), a set of coupled equations must be defined. Each variable in each control volume is associated with a conservation equation. For example, velocity is determined by a conservation of momentum, enthalpy and temperature are determined by a conservation of energy, and so forth.

The selection of equations depends on the processes to be modeled. For the wind flow around a building, equations representing the temperature field as well as different species concentrations are not necessary because it is reasonable to assume perfect mixing. If a study of pollution or moisture condensation is the objective, multiphase equations should be applied. If the airflow is turbulent, an appropriate turbulent model should be selected, that is, either turbulent kinematic viscosity, an algebraic model, a mixing length model, a one equation k-l, or a two equation k-e model. Spalding (1982) gives a general review of the potential and the limitations of these models. The finite domain approach, therefore, has potential applications in several fields of study. The user of this method should judiciously select the equations that are necessary to describe a specific problem, without unduly increasing the complexity and the computer time required for a solution.

The relevant equations are discretised over the entire two- or three-dimensional problem according to different numerical schemes (Patankar 1981). The domain of the study must be closed with adequate boundary conditions applied, for example:

- A perfectly insulated wall implies a zero heat flux condition in the control volumes that are adjacent to the wall.
- An introduction of air into the domain, for example, an open window or a mechanical vent, requires specification of the temperature, the inlet velocity and the momentum at the inlet.

- A conductive coupling of the domain with the outside environment, for example, through a window or wall, requires specification of the conductivity and area of the window or wall, as well as the adjacent outside temperature.
- The presence of a wall or partition implies a zero velocity at the surface, usually called a no-slip condition.

The solution of the set of these linked equations with accurate boundary conditions requires a considerable amount of computer time. However, the advantage is that any variable can be examined at any point in space or time. Thus, it is possible to study the interdependency between physical processes and thereafter either disconnect them to reduce the computer time required for convergence or introduce other processes to improve the accuracy of the solution. This is usually an iterative process that requires both knowledge and experience from the user.

The finite domain method has been extensively used for general fluid dynamics problems and more recently in natural and mixed convection for simplified, single zone buildings (Allard 1986, Whittle 1986). In building analysis, the emphasis has been on evaluation of the heat transfer exchange at each physical surface and on air movement inside the zone. This technique dynamically calculates the heat transfer coefficient along each surface by simultaneously solving the enthalpy and Navier-Stokes equations. A recent study (Altmayer et al. 1983) concluded that the heating loads of a building can be over or underestimated by up to 50% by using standard convective coefficients (ASHRAE 1985) rather than calculated coefficients.

In existing building energy codes, airflow is either explicitly specified by the user, as in BLAST (CERL 1979) or DOE-2 (BESG 1985), or is driven only by bulk density differences, as in the mass balance approach used by ESP (Clarke 1985) or TARP (Walton 1983). In neither case is it possible to properly account for airflow driven by boundary layer pumping or by unstable stratification (Kirkpatrick and Bohn 1985, Anderson 1986). Likewise, the effects of partitions or obstacles are difficult to analyze with existing codes and they may have considerable impact on the air circulation inside of a building.

To illustrate a typical difference between the mass balance and the finite domain approaches, we simulated airflow in the two room configuration shown in figures 4 and 5. Ventilation air enters through a window, passes through a door separating the two rooms and then exits through the other window. We obtained the indicated results with the finite domain model CONVEC (Fleury 1986) using assumptions of constant air temperature and laminar airflow. The vectors in figure 4 show the direction and relative speed of the air at each point; the longer the vector, the faster the air is moving at that point. The streamlines shown in figure 5 can be interpreted as similar to the smoke that is commonly used in wind tunnel visualization tests.

As shown in both figures, the wall separating the two zones has caused significant short-circuiting of the airflow, with both inactive areas and relatively high local velocities. This design can lead to occupant discomfort because of both inadequate air movement at certain locations as well as excessive velocity at other locations. A simulation of this design using the mass balance approach would not indicate any potential problems, because of the inherent assumption of perfect mixing of the air in each zone. The designer would be able to determine only the airflow rate between zones, with no indication of the distribution within each zone, perhaps concluding that the average velocity is adequate for comfort.

CONCLUSION

At the present time, no comprehensive building energy simulation program utilizes the finite domain method because of the excessive computer time required for a solution of the conservation equations. However, in future years, it is likely that the rapid development of high speed computers and improved numerical solution techniques will enable this method to be used for detailed, multi-zone, building analysis, fully accounting for the effects of natural and mechanical ventilation. In the interim, we believe that the finite domain approach should be used for selected problems (e.g., possible air stagnation, short-circuiting, etc.), to provide valuable insight to the building designer about potential inaccuracies of the mass balance approach. For those design problems where it is suitable, the mass balance approach remains a significant improvement over more simplified methods that are still in common use.

ACKNOWLEDGEMENTS

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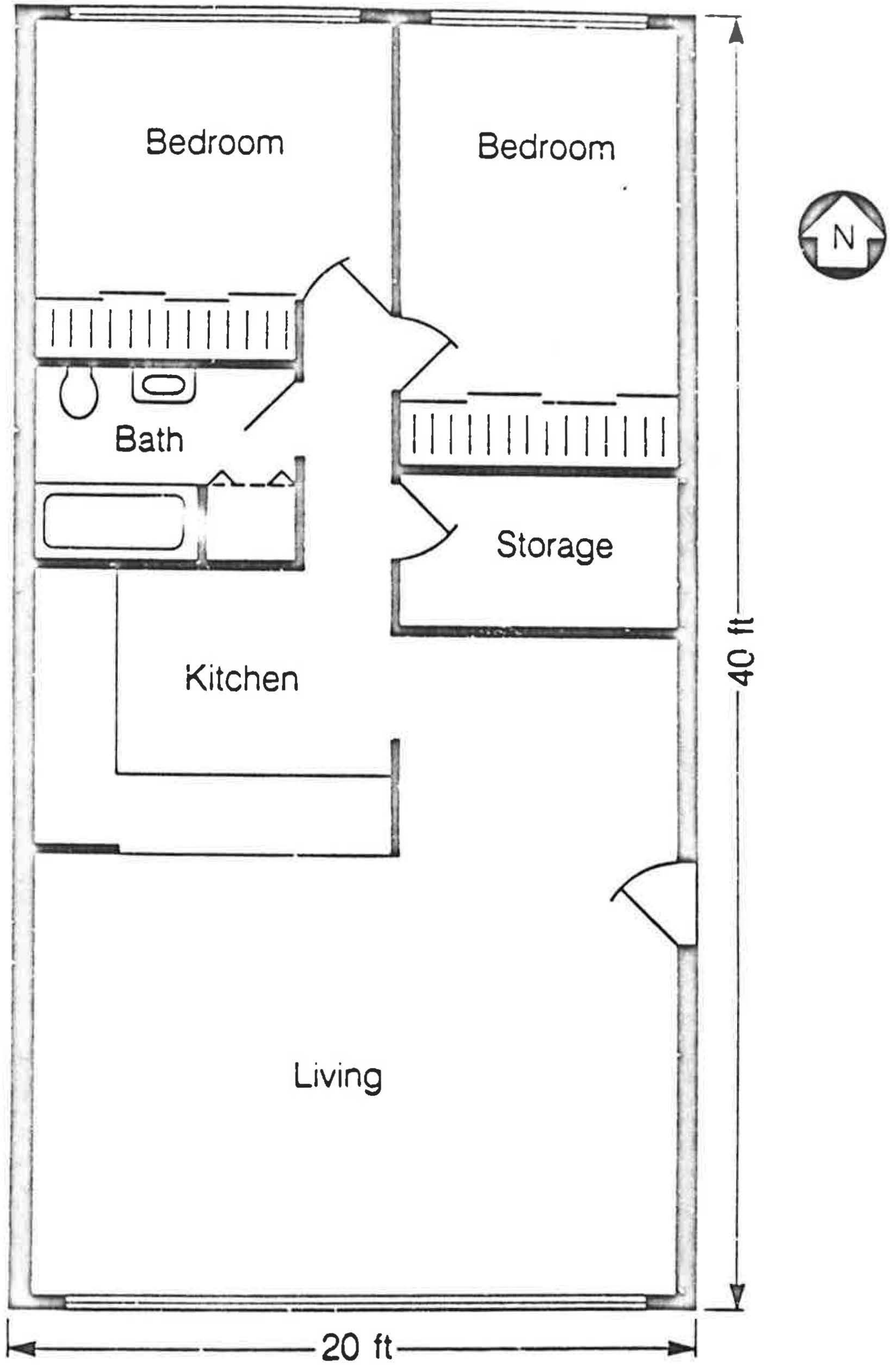

Figure 1. A typical apartment floor plan used to illustrate application of the mass balance approach to airflow analysis

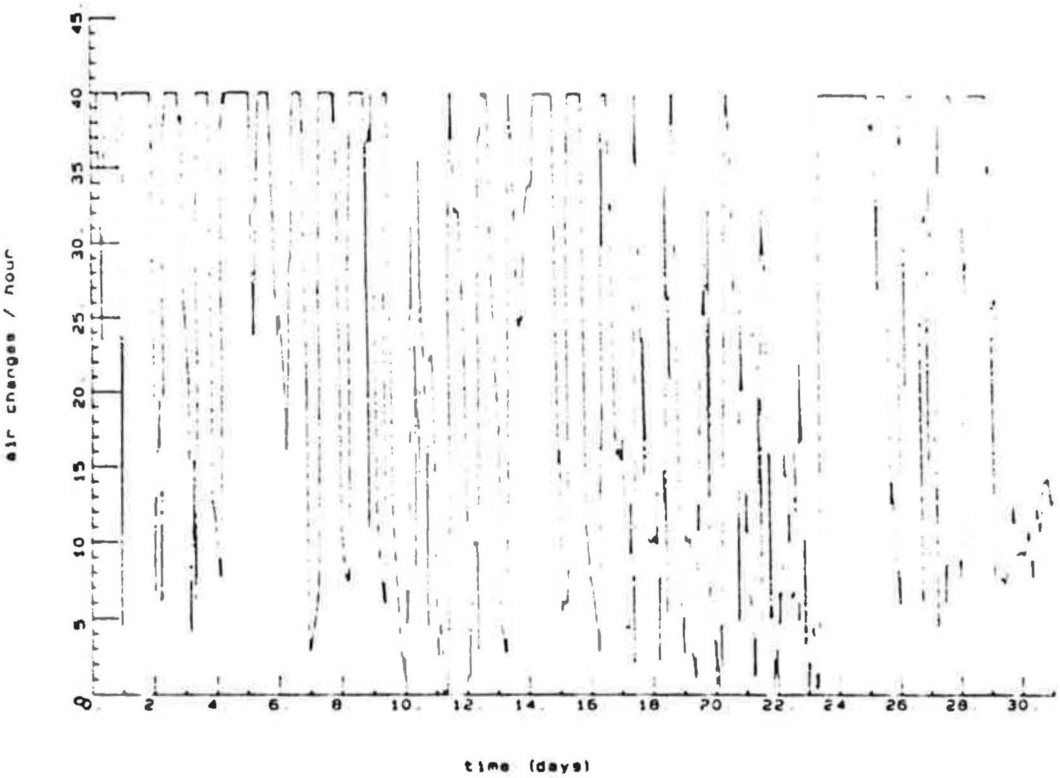

Figure 2. Simulated airflow rate through the living room of the apartment shown in Figure 1; these results are for the month of January in Noumea, New Caledonia

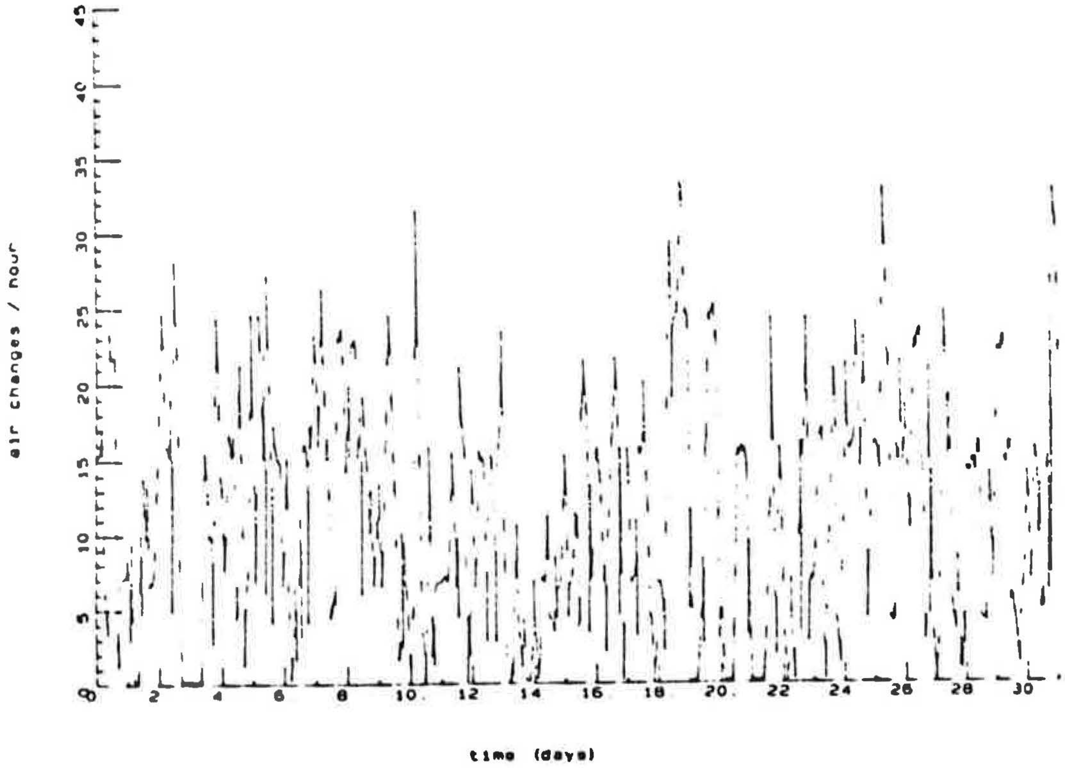

Figure 3. Simulated airflow rate through the living room of the apartment shown in Figure 1; these results are for the month of January in Poindimie, New Caledonia

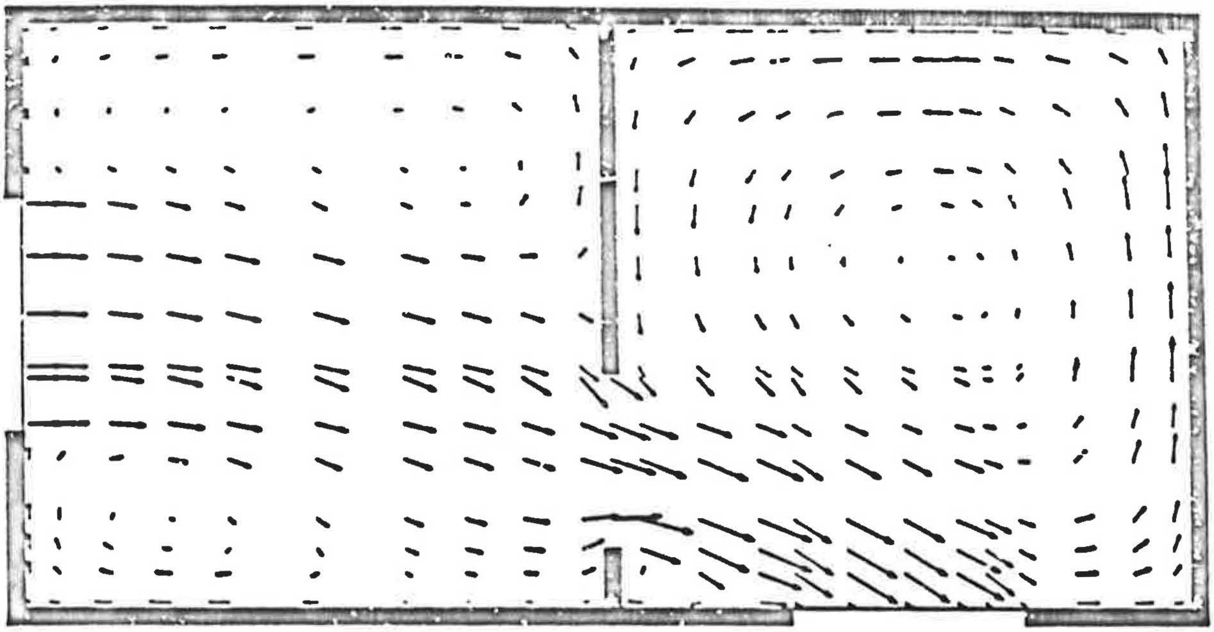

Figure 4. Simulated airflow using the finite domain approach. Vectors represent direction and speed at each point; the longer the vector the faster the air is moving at that point.

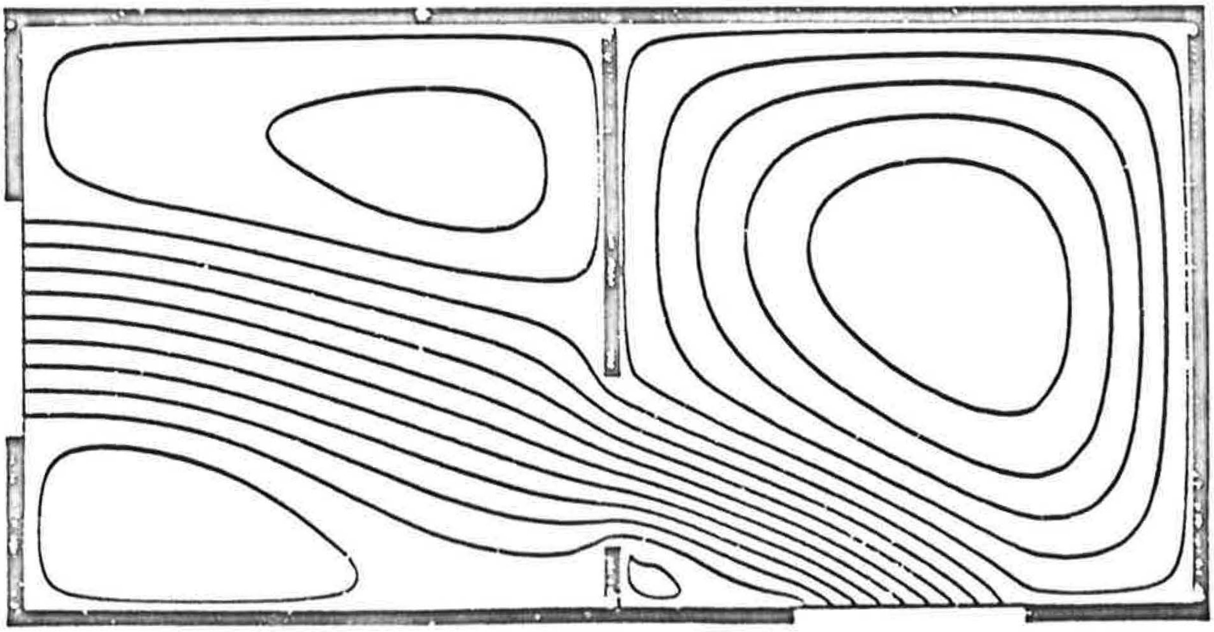

Figure 5. Simulated airflow using the finite domain approach. This is the result of the same simulation as in Figure 4 using streamlines to represent airflow.