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The Simulation Of Infiltration Rates And Air Movement In A Naturally Ventilated Industrial Building.

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SYNOPSIS

This paper describes the application of numerical models to predict the ventilation rate and internal air movement patterns for a naturally ventilated industrial building and compares the results with measured data.

Two modelling techniques have been employed. Firstly, a zonal network model (HTBVent), using leakage area data derived from fan pressurisation measurements, was used to predict the time varying ventilation rate in response to variations in wind velocity and internal-external air temperature difference. The results compare well with measurement data (obtained using constant concentration tracer gas techniques) over a wide range of ventilation rates. The results demonstrate the use of zonal models to estimate the thermal benefits of applying sealing measures to building components.

Secondly, a computational fluid dynamics (CFD) model (DFS-AIR) was used to predict the ventilation rates and also the internal air movement resulting from natural ventilation, for selected external conditions. The predicted ventilation rates again agree well with measurement data. The resulting air movement patterns can be used to indicate the effectiveness of natural ventilation and the implications for comfort throughout the occupied space.

The general conclusion was that these modelling techniques, having been successfully tested against measurement data, can be used in the design of naturally ventilated buildings.

1.0 INTRODUCTION

This paper describes the use of computer models to predict firstly the overall air infiltration rate of the building (using a zonal model called HTBVent) and secondly the internal air movement paths resulting from natural ventilation (using a CFD model DFS-AIR).

The ventilation performance of a factory was extensively monitored over the summer of 1988 and reported on at the 10th AIVC conference [1]. Air infiltration rate data was collected by a continuous constant concentration technique over a wide range of climatic conditions and building sealing levels, whilst air leakage data was obtained by fan-pressurisation and reductive sealing techniques.

The results from the air leakage experiments were used to quantify and locate major sources of air leakage over the building envelope. This information was then used as input data for the ventilation models. The zonal model was used to predict the variation of ventilation rate of the building over time using recorded values of wind speed and direction, internal and external air temperatures, together with suitable wind pressure coefficients for each wind direction. The predicted air infiltration rate was then compared with measurement data over a period of time.

The air leakage data was also used as input data for the CFD model which was used to predict the air infiltration rate and internal patterns of air movement under selected wind and stack conditions.

2.0 TEST BUILDING

The test building was a detached factory with a production space floor area of 466 m^2 and a production space volume of 3050 m^3. Figure 1 contains a floor plan and section of the factory.

The factory walls had an inner skin of masonry and an external skin of profiled metal cladding. The roof had the same external metal cladding with an inner skin of fibreboard. Both constructions incorporated glass fibre quilt insulation to give a U-value of 0.6 $W.m^{-2}.K^{-1}$. The factory was built on a concrete slab base. There was an internal office space which was partitioned off from the production area.

Double glazed windows occupied 7.5% of the total wall area. There was approximately 10% rooflighting. There were also 4 louvered roof vents fitted, each of area 1.56 m^2.

The factory was fitted with a single standard roller shutter loading door of approximate area 16 m^2. The loading bay door faced north, the factory being orientated on an east-west axis.

3.0 MEASUREMENTS

3.1 Air Leakage

Air leakage tests were performed using the fan pressurisation technique. The pressurisation unit was a modular system based on two fan and duct units that were fitted into one of the fire doors. This allowed component testing of the main loading door to take place. The volume flow rate through the ducts were measured using Wilson Flow Grids. The volume flow rate could be varied by means of speed controllers fitted to each fan; the maximum flow rate achievable, with both units at full speed, was 8.4 m^3s^{-1}.

3.2 Air Infiltration Rate

Air infiltration rate tests were performed using constant concentration tracer gas techniques employing the Autovent System developed and marketed by British Gas plc [2].

The constant concentration tests were performed using pure nitrous oxide (N_2O) as the tracer gas. A target concentration of 50 ppm was used. The building was divided into 5 controlled zones for these measurements. A cycle time of 6 minutes was used, and the raw results were amalgamated to provide 30 minute data records.

3.3 Experimental Programme

The air leakage (fan pressurisation) and air infiltration (constant concentration) experiments were carried out during July and August 1988.

Three pressurisation measurements were undertaken; the factory "as-built" (test P03), with the loading door sealed (P01), and with the loading door and roof vents sealed (P02).

Eight constant concentration tests (designated CC01 to CC08) were performed. Tests CC01 through CC06 were carried out on the factory "as-built". Test CC07 was carried out with the loading door sealed. Test CC08 was carried out with both the loading door and ventilators sealed.

The results have been reported in detail in an earlier paper [1]. Air leakage tests P01,P02 and P03, and constant concentration tests CC01 to CC06 have been used in this investigation.

The "as-built" data sets CC01 to CC06 comprised 374 half hourly records of internal and external temperature, wind speed and dominant wind direction, and the measured air infiltration rate. These encompassed a wide range of conditions of stack effect (1.6°C to 15.7°C temperature difference), wind speed (0.3 ms^{-1} to 7.6 ms^{-1}), and resulting air infiltration rates (0.2 $Ac.h^{-1}$ to 1.0 $Ac.h^{-1}$). The wind directions were predominantly southerly, but included some cases from all quadrants.

4.0 MODELLING

4.1 Zonal Model

The infiltration model used for this work was HTBVent, a multi-zone, nodal network model based on that described by Etheridge and Alexander [3].

This model calculates the airflow across the cracks or openings in the building fabric according to their geometry, position and external pressure forces. It differs from other similar models [4,5] through the use of "crack-flow" equations [6], rather than the more typical exponential best fit method. The "crack-flow" equations are based on a quadratic relationship between airflow and pressure difference :-

$$\Delta P = \alpha Q^2 + \beta Q,$$

where, Q is the flow in m^3s^{-1},
ΔP is the pressure difference in Pa.

This form of relationship allows the transition of flow though small openings, from laminar to turbulent, to be handled correctly, whilst also allowing large orifice-type openings to be specified.

The parameters α and β are determined from the physical dimensions and the geometry of the opening :-

$$\alpha = \frac{C\rho}{2A^2}$$

$$\beta = \frac{B\rho\nu DL^2}{8A^3}$$

where, ρ is the air density, Kgm^{-3},
ν is the air viscosity, Nsm^{-2},
A is the crack open area, m^2,
L is the crack length, m,
D is the crack depth, m,
B and C are empirical constants.

The constants B and C are determined by the form of the crack, for instance an "L" shaped opening provides the values 91.36 and 2.20 respectively [6].

In HTBVent, the non-linear network of such crackflow relationships, which describes the building, is solved for pressure and flow by a simple Newton-Raphson scheme. Each solution described in this paper required less than 0.2 second on a 80386/80387 MSDOS PC.

4.2 CFD Model

A 3-dimensional Computational Fluid Dynamics (CFD) model, DFS-AIR, was used to simulate the air infiltration and internal air movement resulting from the effects of a single wind direction on the external fabric of the building with air leakages comparable to those used in the zonal model, only located in 3-dimensional space.

The model is based on the SIMPLE method [7] for solving numerically the equations for the conservation of momentum (ie. Navier Stokes equations), the conservation of mass and the conservation of energy. In this case a simple 'fixed viscosity' turbulence model was used. An internal/external air temperature difference corresponding to the experimental data was achieved by specifying an appropriate fixed amount of heat flux input to the bottom layer of the solution domain. Pressure boundaries at air leakage sites were modelled using the same effective areas as determined by the crack flow equations that were used in the zonal model. The CFD model used a linearised form of the power law equation :-

$Q = \rho KA(\Delta P)^n$ where, ρ is the density of air, Kgm^{-3},
A is the crack area, m^2,
K is an empirical flow coefficient calculated from the above crack flow equations for each leakage area modelled.

The model used a grid of 30x30x35 cells to describe the solution domain. Air leakages were prescribed to occur over a whole cell face at the leakage locations.

The model was run on a 33MHz "i860 Number Smasher" microprocessor based on an 80486 MSDOS PC, which achieved a run time speed of 30 s per iteration

5.0 DERIVATION OF CRACK PARAMETERS

5.1 Data Requirements

In order to run both the zonal and CFD models two sets of information needed to be established.

(i) Crack Characteristics
The physical description of the openings in the building fabric must be determined, in terms of their area, length, depth and type (i.e. straight, kinked, or complex), and then each such opening must be "placed" on the building envelope.

In this work this data was derived from air leakage measurements.

(ii) External Wind Pressure
Surface wind pressures may be determined by site measurement, wind-tunnel measurement, numerical modelling, or simplified algorithms.

In this work the latter were used. Wind pressure coefficients were calculated from the algorithm developed by Swami and Chandra [8]. This algorithm provides generalised surface average coefficients solely from wind direction.

5.2 Crack Flow Characteristics

The data required for the description of the openings of the building was produced by analysis of pressurisation test results. In the case discussed here, the pressurisation data available was;
Test P01- the envelope with the loading door sealed,
Test P02- the envelope with the loading door and roof vents sealed.
Test P03- the whole building envelope "as built",

This data was used in the following way;

A log-log best fit model was produced for these 3 pressurisation tests, as shown in figure 2.

These empirical models were then used to produce, by subtraction, the estimated leakage characteristics for,
- the total background, (Test P02),
- the loading door (Test P03 - Test P01), and
- the roof vents (Test P01 - Test P02).

Each of these characteristic curves (figure 3) were then fit to the quadratic "crack-flow" relationship, to produce the α and β parameters described above. These parameters in themselves are sufficient to proceed, but given logical constraints (i.e. the background leakage is likely to be of a complex type with a length comparable to the dimensions of the envelope) a reasonable set of values for crack area and length may be estimated.

The final disaggregation was checked by calculating, for known pressures, the total flow predicted and comparing this to the measured envelope leakage. This comparison is shown in figure 4. The agreement was considered to be good.

5.3 Crack Locations

The above procedure produced lumped open areas, however it did not identify the location or composition of those openings. For both the zonal and CFD models to be used, the open areas identified must be assigned to appropriate facades and attributed a physical location.

In this case the locations of both the loading doors and the roof vents could be easily identified. There were four vents, located high on the north and south facing roofs and a large loading door on the north facade.

The background leakage is by definition the leakage which is not attributable to a single component. A logical distribution of that leakage area was assumed, in relation to the simple construction of the building. In particular, there was no indication that the facades would be unduly asymmetric; and so is one quarter of the total background was applied to each of the north, south, east, and west faces of the building. Further, the construction type used could be assumed to be have continuous crackage near the location of the main constructional details, i.e. the eaves.

6.0 RESULTS

6.1 Zonal Model

The zonal model was subjected to the full "as-built" data set: CC01 through to CC06.

A number of leakage distributions were considered, each making different assumptions as to the location of the background leakage. Overall, most distributions which were thought reasonable (i.e. those which were not unduly asymmetric between the wall and roof leakage areas) produced an agreement range, over the entire data set, of approximately - 0.05 + 0.25 $Ac.h^{-1}$. There was some tendency to over-predict infiltration for the higher wind speeds.

The best agreement was achieved with a distribution based on the assumption that the majority of the background area would be found near the eaves. This is illustrated in figure 5. The agreement, as in figure 6, was very good; 90% of the values are within ± 0.10 $Ac.h^{-1}$ of the measurements. There was no correlation between the error and any of the data parameters; wind speed, direction, or temperature difference. The agreement was felt to be approaching the measurement accuracy of the system.

The agreement between prediction and measurement for dynamic time-series data is illustrated in Figure 7, for this final distribution. This figure shows the measured and predicted infiltration rates over a continuous three day period (test CC05). The model appeared to adequately follow the rapid changes of the building air infiltration rate.

The utility of such a model lies in the ease of determining the impact of changes to the building fabric. For example, the effect of sealing the loading door may be assessed. By removing the doors leakage definition from the data file and then recalculating, it was estimated that the infiltration rate would drop on average by 0.12 to 0.14 $ac.h^{-1}$, over the total period of the measurements. This was in good agreement with the decrease actually observed during the measurement project in test CC07 [1].

6.2 CFD Model

The CFD used the same crack specifications as determined for the zonal model.

The CFD model was run for a single point in time, when the wind speed was 2.1 ms^{-1} from the south. The internal air temperature was 21.7°C while the air temperature outside was 20.1°C.

The first simulation was carried out assuming no internal/external air temperature difference. Figure 8 shows a north-south section centre to the factory. The overall air change rate was calculated as 0.218 $Ac.h^{-1}$, which compared well to the measurement value of 0.22 $Ac.h^{-1}$. The air flow paths can be seen with the main inflow of air at the windward facing eaves and the main outflow through the relatively leaky 'closed' roof vent. There is a small airflow through the windward facing roofvent even though there is a slight negative external pressure at this point. It should be emphasised that the predicted air velocities are very low for this simulation.

The second simulation included the effects of the 1.6°C internal/external air temperature difference. The results are shown in Figure 9. The overall air change rate was calculated as 0.217 $Ac.h^{-1}$, which is not significantly different from the first case. However, it can be seen that the air movement set up by wind driven air leakage is now completely masked by the internal air movement due to the buoyancy effects (which are relatively small), and the predicted air velocities are typically an order of magnetude higher than for the isothermal case above.

7.O CONCLUSIONS

The calculation of infiltration rates, made with a zonal air infiltration model, have been found to be in good agreement with measured values, even though only a generalised wind pressure coefficient algorithm and a simple series of envelope leakage measurements were used as input data. Fine tuning of the assumed background leakage locations, in the light of the measured infiltration rates, produced a model that was able to predict to within ±0.1 $Ac.h^{-1}$ over 90% of test cases, encompassing a range of 0.2 to 1.0 $Ac.h^{-1}$.

The model was successful in estimating the impact of altering the building fabric, i.e. sealing the loading door.

After a wider validation, such a technique could be useful in assessing the ventilation performance of factory or similar buildings, from a simple set of air leakage measurements.

Comparisons with the CFD model indicated that the CFD model could be used to predict air infiltration rates using crack flow equations. Such a model also enabled the air flows inside the space to be visualised. This could be used to predict ventilation effectiveness and comfort conditions. It appeared, for the conditions simulated, that although wind effects dominated the determination of the air infiltration rate, relatively small buoyancy effects could determine the overall internal air movement pattern.

ACKNOWLEDGEMENTS

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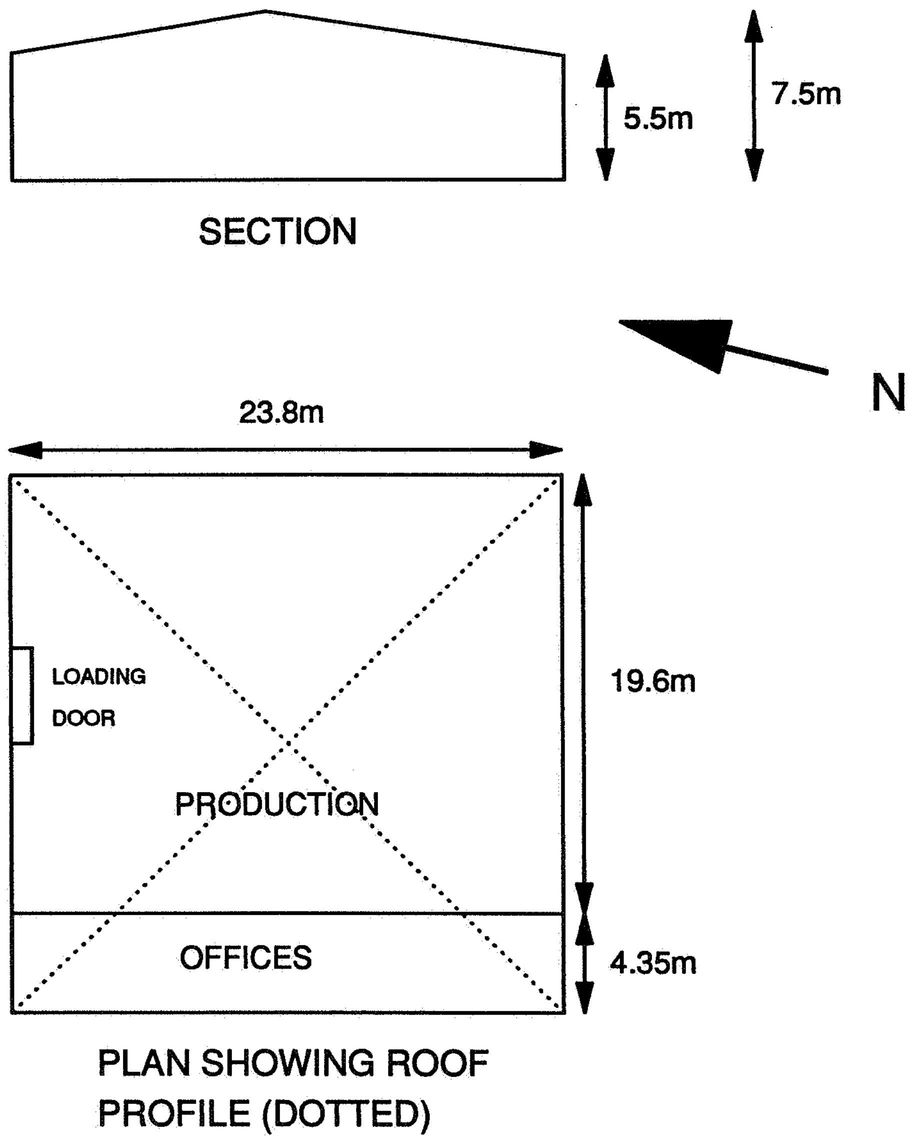

Figure 1: Plan And Section Of Test Factory.

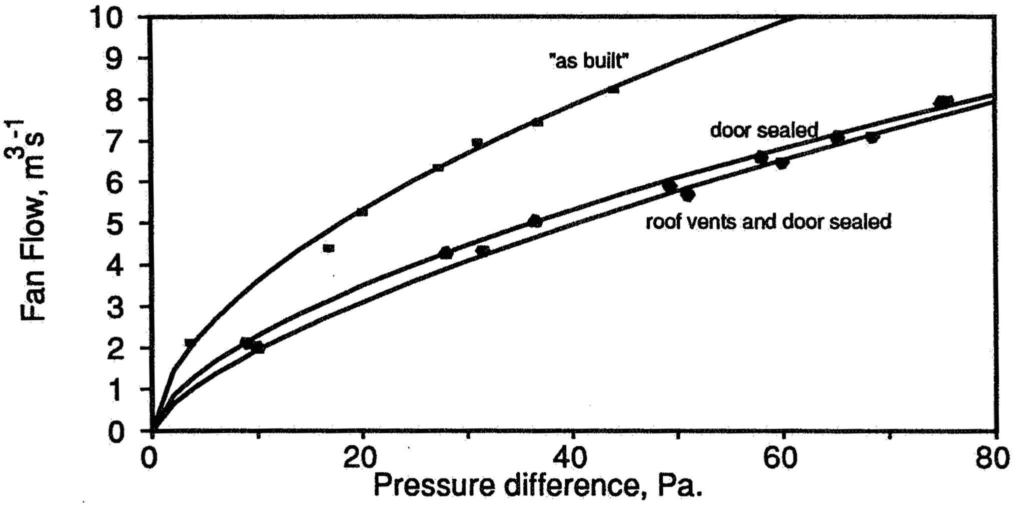

Figure 2: Pressurisation Test Results, Log-Log Regression.

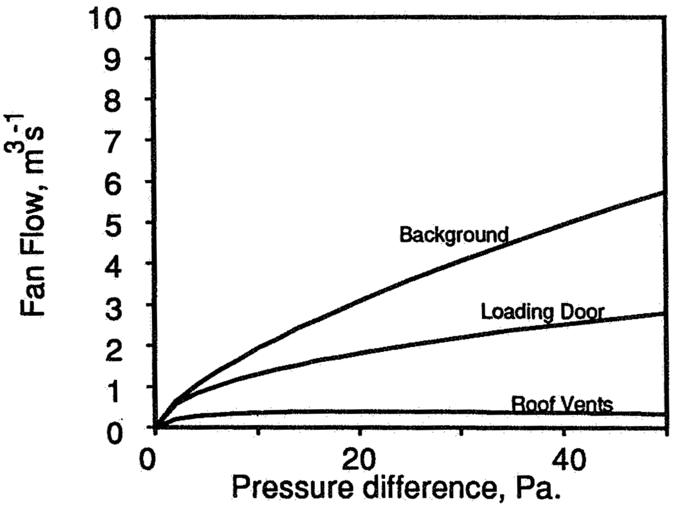

Figure 3: Component Leakages Estimated by Subtraction.

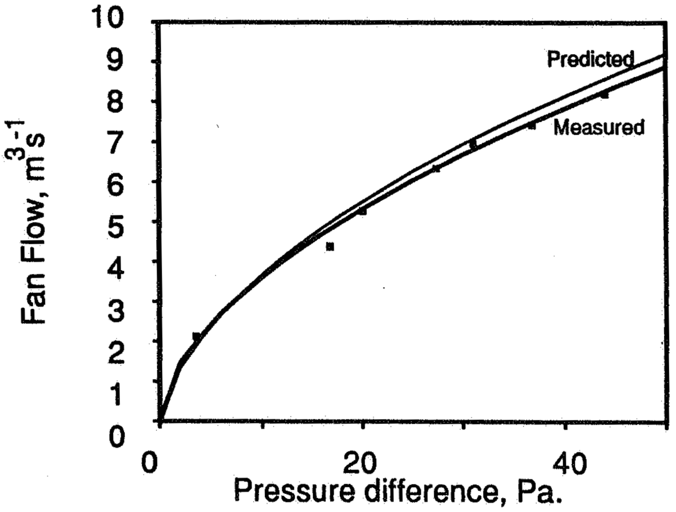

Figure 4: Comparison of Measured and Modelled Leakage.

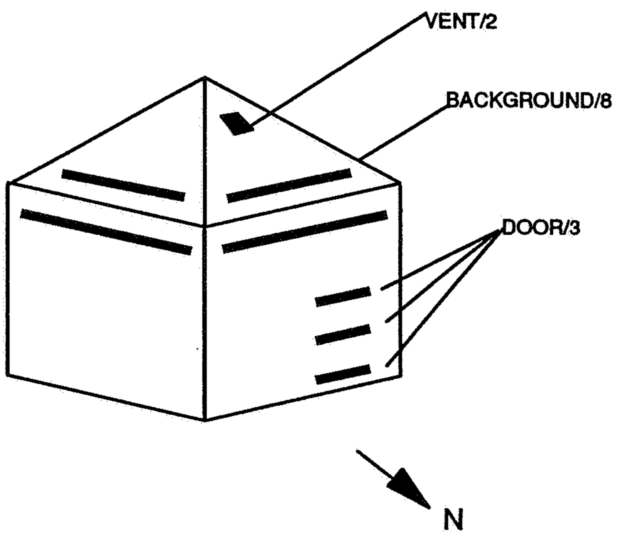

Figure 5: Schematic Of Leakage Areas For 'Best' Distribution.

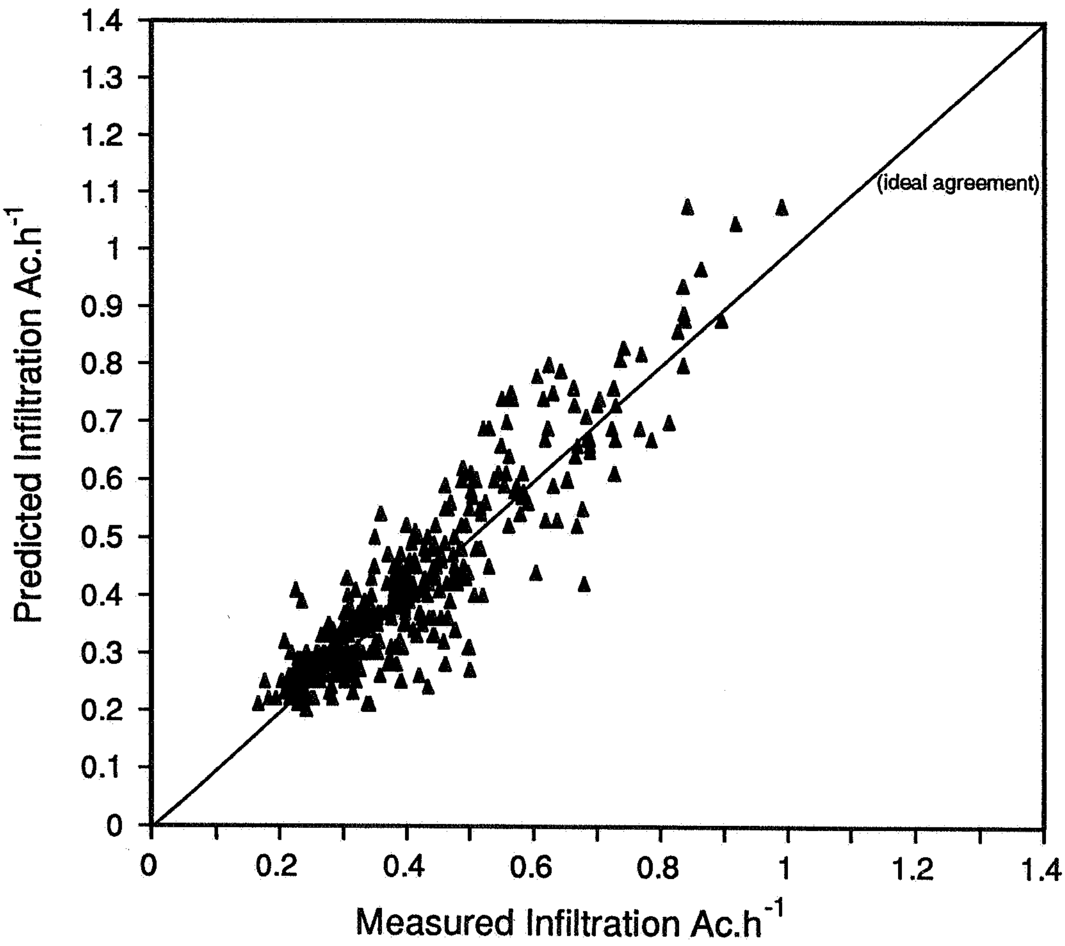

Figure 6: Comparison of Modelled and Measured Infiltration.

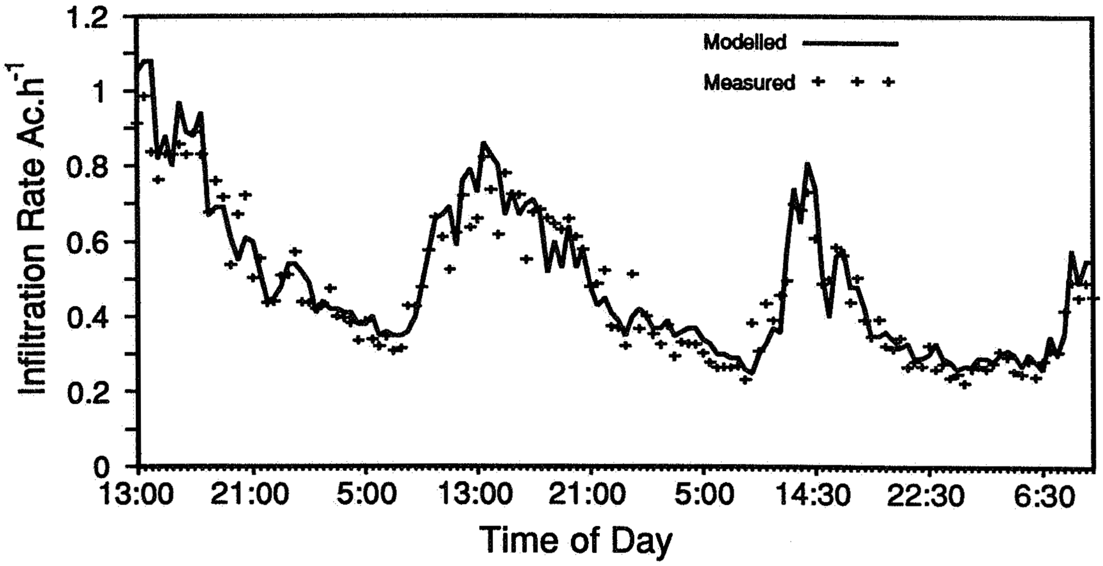

Figure 7: Time Series Comparison for Test CC05.

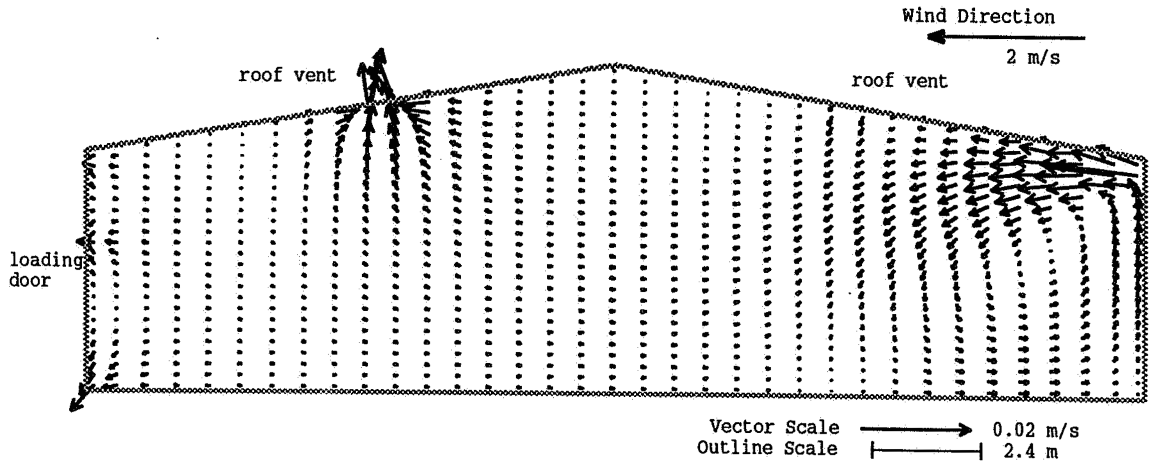

Figure 8: Internal Airflow Modelled with No Stack Effect.

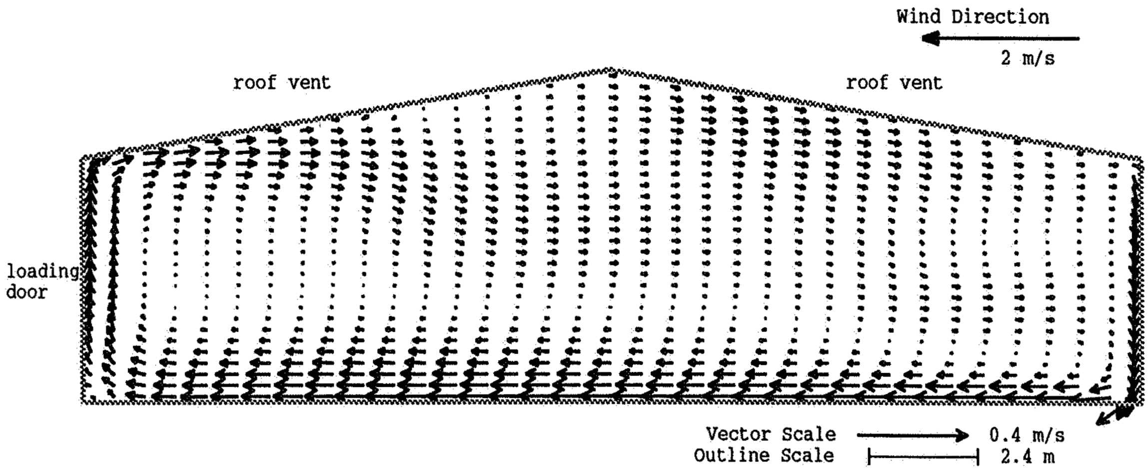

Figure 9: Internal Airflow Modelled with Stack Effect.