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Convection and infiltration modelling for the built environment

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KEYWORDS

Building Thermal Simulation, Convection, Infiltration

ABSTRACT

It is now widely recognised that in order to develop realistic methods for the energy-conscious design of buildings, it is necessary to replace the traditional steady-state procedures by ones which model the dynamic thermal response of the system. However, these dynamic models are particularly sensitive to the input values assigned for convective heat transfer coefficients and air infiltration rates. The author has, consequently, developed a set of intermediate-level computer programs for calculating the external convection heat transfer coefficients around buildings and the air infiltration rates into them. These computer codes were employed for performing a comparative analysis on the NBSLD response factor program. The NBSLD thermal model displayed a considerable sensitivity to the intermediate-level computer codes, although the extent of the impact of these codes is likely to depend on the conditions prevailing in and around the simulated building.

Convection et l'infiltration modèles réduits pour l'environment

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MOTS-CLÉFS

Convection, Infiltration, Simulation du Bâtiment Thermique

SOMMAIRE

Il est à présent généralment reconnu que pour déveloper des méthodes réalistes pour la conception des bâtiments qui sont énergie-conscients, il est nécessaire de remplacer les conceptions traditionnelles d'état-stable pour celles qui modèlement réponse dynamique thermique du système. Cependant, ces modèles dynamiques sont particulièrement sensibles aux valeurs absorbées attribuées au coefficient de transmission de chaleur pour la convection et a la vitesse de l'infiltration. Par conséquent, l'auteur a dévelopé une série de programmes d'ordinateur au niveau intermédiaire pour calculer les coefficents de transmission de chaleur extérieure par la convection tout autour des bâtiments et les vitesses de l'infiltration dans les bâtiments. Ces codes d'ordinateur out été employés pour évaluer la sensibilité de le programme pour la réponse facteur du NBSLD. Le NBSLD modèle thermique réduit ont montré une sensibilité considérable aux codes ordinateur des niveau intermédiaire, bien que la mesure de l'impact de ces codes dépende probablemt des conditions dominantes dans le bâtiment simulé aussi bien tout autour.

1. INTRODUCTION

A comprehensive study of the new generation of dynamic building thermal models by the International Energy Agency |1| concluded that their accuracy is presently limited by uncertainties in the input data, particularly for air infiltration and convective heat transfer rates. The emphasis in these modern models is placed on simulating the thermal performance of the building fabric, whereas convective heat exchange and air infiltration rates are modelled using rather crude approximations. In an attempt to overcome this problem, a set of intermediate-level sub-system models for calculating the external convective heat transfer coefficients around buildings and the hourly mean rates of air infiltration into them has been developed |2|.These intermediate-level computer codes, together with the ROOM-CHT program developed by Alamdari and Hammond |3| for estimating the convective heat transfer coefficients on the internal surfaces of mechanically-ventilated buildings, were employed to perform a comparative analysis on a well-tested dynamic model developed by the US National Bureau of Standards |4|. The mathematical formulae on which each intermediate-level sub-system model is based have been kept to a minimun in order to conform with the space limitations, although full details are reported elsewhere |2, 3, 5-9|.

2. EXTERNAL CONVECTION FROM BUILDINGS

Design guides in Britain |10| and America |11| provide simple methods of estimating the exterior convective heat transfer coefficient over buildings, although these cannot accurately reflect the complex mechanism of heat transfer over the whole of a buildings' surface. These methods take no account of the predominant wind direction, the change in shape and height of the atmospheric boundary layer over different terrain, or the relative dimensions of the building. Nevertheless they are commonly adopted for use in building thermal models.

In an effort to obtain improved predictions, an intermediate-level model for external convection has recently been developed and incorporated into a computer program called the WIND-CHT (Wind-induced Convective Heat Transfer) Code |2|. Here the computer is employed to generalise available data correlations for the individual flow regimes that prevail around buildings, such as stagnation, boundary layer, and separated flows. These equations yield the surface-averaged heat transfer coefficient in a Nusselt number (Nu) relations of the form:

$$Nu = Nu(Re\ , Pr) \qquad (1)$$

Where Re is the corresponding Reynolds number, and Pr is the Prandtl number. The wind profile is computed using a power-law expression in which the index depends on the local topography. Three shapes were chosen to represent open country, suburban areas and city centres following the recommendation of Davenport |12|. The velocity scale used in the WIND-CHT program to determine the appropriate Reynolds number, is the integral value obtained from the wind profile over the area of building surface of interest. This is more logical than the common, but arbitrary, practice of adopting the wind speed at 10 metres above ground as the velocity scale. Standard data correlations of the form of equation (1) were chosen for all the "pure" flow regimes, except the stagnation flow on the windward surface. Sogin's relation |13| was adopted for the separated flow in the lee of the building. An interpolation formula similar to that employed by Alamdari and Hammond |7| was used to generate,from standard correlations, an expression for the side-wall boundary layers which is valid for laminar, transitional and turbulent flow. Unfortunately, laboratory-scale correlations for the stagnation flow, such as that proposed by Sparrow et al |14|, were found to be unrepresentative of the, albeit very limited, field measurements. This is probably due to the combined influence of high wind turbulence intensity, and building ground interaction effects |15-18|. A new power-law correlation was therefore developed |2| from the field measurements on office buildings by Ito et al |19| and by Sharples |21|, although these data sets display a wider variation between themselves than would have been desired. The final component of the WIND-CHT program is the weighting function used to interpolate convection coefficients for wind directions that are non-orthogonal to the building surfaces. A simple cosine squared function was adopted as this gave a plausible variation between the various combinations of the pure flows, in the absence of reliable field measurements. These combinations consist of stagnation flow/boundary layer interactions on the windward surfaces, and boundary layer/separated flow interactions on the leeward ones.

The capabilities of the WIND-CHT program are illustrated by Figure 1, where its computations for the city centre multi storey Arts Building at Sheffield University are compared with Sharple's data |20|. The WIND-CHT program yields only the average heat transfer coefficient on the facade, which in this particular case is 36 metres long. The computations are therefore considerably higher than the experimental results taken at the mid-position and conversely lower than those taken at the edge of the facade.

3. AIR INFILTRATION RATES INTO BUILDINGS

The lack of an adequate method for estimating the infiltration heat loss from a building constitutes another major deficiency in the present generation of building thermal models. Two methods are commonly adopted by modellers for estimating air infiltration rates into buildings. The first, and most widely used, is the air change method, which is an entirely empirical technique. The second popular method for estimating infiltration rates employs empirical correlations between infiltration rates and weather data, usually based on long-term field measurements. Such methods usually result in over-estimating the plant capacity. It is therefore necessary to improve on these methods, as an over-estimation of plant capacity would lead to unnecessarily high investments and reduced efficiency.

Many computer programs have been developed in order to calculate infiltration. However most models presently in use are either not within the public domain or are written as research tools, rather than for meeting the needs of dynamic building thermal models. In order to overcome this problem a computer program, called FLOW, has been developed. This code differs from previous calculation methods in that the wind pressure coefficients, and consequently the pressure distribution around the building, are determined internally. In doing so, it accounts for the nature and roughness of the surrounding terrain and the consequent atmospheric boundary layer, the wind speed and direction, the building proportions and for any external shielding. Two different techniques based on wind tunnel results are then employed. The first technique was developed from Bowen's experimental results [21]. It can be used for calculating the wind pressure coefficients when the average height of the adjacent structures, Ha, is in between 16% and 100% of the heigh of the building itself, Hb. Bowen's results were fed into a computer routine and by using the Lagrange interpolation technique the wind pressure coefficients for any height across any wall and for any wind angle are then calculated. The results thus obtained are related to a minimum degree of shielding of $Ha/Hb = 1/6$, and a correction factor of shielding has then to be applied. If a flow exponent, n, of 0.65 (generally accepted for cracks) is assumed, the air flow correction factor of shielding, Fc, presented by shaw [22] reduces to:

$$F_c = (C_p)_{Ha/Hb}/(C_p)_{1/6} = 1.24\ e^{-1.31Ha/Hb} \qquad (2)$$

where Cp is the wind pressure coefficient.
The second technique considered was the "harmonic analysis" method presented by Allen [23]. Allen showed that the mean wind pressure coefficients for any symmetrical building can be represented by a Fourier series. The series coefficients are dependent on the aspect ratio and on the degree of shielding. It was decided to use this technique only for exposed structures ($Ha/Hb < 1/6$), since very good estimates of the wind pressure coefficients for sheltered buildings ($1/6 < Ha/Hb \leq 1$) were obtained by using the first technique. The Fourier series takes the following harmonic form:

$$Cp(\Theta) = a_o + \sum_{n=1}^{7} a_m \cos(m\Theta) \qquad (3)$$

where Θ is the wind angle of attack. The coefficients, a_m, are given by Allen [24].

The FLOW program can be run using either a single cell approach, in which the interior of the building is assumed to be a single uniform pressure, or as a multi-cell model. In the latter case, the interior is subdivided into zones of differing pressure interconnected by leakage paths. The internal pressures are calculated assuming that the amount of air entering each limited space, or zone, of a building through cracks is equal to the amount of air escaping from the zone. Thus, the basic mathematical procedure is to obtain a solution to a set of pressure difference equations of the following type:

$$\sum_{i=1}^{m} C_{i,j}\ (Pi - Pj)^{n_{i,j}} = 0 \qquad (4)$$

where $C_{i,j}$ and $n_{i,j}$ are the flow coefficient and flow exponent applicables to the air flow between the spaces i and j respectively, and m represents the total number of air flow paths of node j. Typically building networks will have a large number of flow paths, consequently matrix methods for solving the non-linear set of equations would currently be cumbersome and expensive in terms of computing requirements. The Newton-Raphson iterative technique for multiple equations and unknowns has, therefore, been adopted for the FLOW program.

An important part in the development of any air infiltration model is to determine the limits of its accuracy by comparison with field measurements. To assist in this task Liddament and Allen |24|prepared three key data sets so that the full range of applicability of any model being tested can then be assessed. The first data set is based on measurements made in an isolated, detached dwelling in Switzerland, the second in a detached dwelling in Otawa, Canadã and the third in a mid-terrace, three storey dwelling in Runcorn, UK. Liddament and Allen |24| suggested that the model performance should be considered satisfactory if the computational results fall within ±25% of the measured infiltration rate. Good agreement between the calculation and measurement, for the Swiss house, was achieved. With all but three (actually 83%) of the calculations being within 25% of measurement. Consistent agreement was also obtained for the Canadian house, with 37 of the 49 values (75%) falling inside the 25% band. The results obtained for the British house were also consistent, with 11 of the 15 (73%) calculated values being within the specified tolerance bands. Due to space limitations only the results for the Canadian house are presented in Figure 2.

4. COMPARATIVE ANALYSIS ON THE NBSLD PROGRAM

Unfortunately, no field measurements appear to be available to facilitate a proper validation study. It was therefore decided to perform only a comparative analysis on the NBSLD program by adopting a "hypothetical" detached house broadly based on the multi-layered construction of the 3-bedroomed, terraced houses in Livingston, Scotland that were studied by Clarke and Forrest |25|. In addition, a ground floor insulation slab was included to reflect a "heavy" (or thermally "massive") structure, while the height of each room in the two-storey dwelling were assumed to be 2.8 metres.

In order to simulate the heating load for a typical winter day within the Livingston "test house", meteorological data for Kew, London ($51^{o}28'$N,$0^{o}19'$W) on the 21st December 1964 was employed. Where the calculations were performed for the "whole" heating season, meteorological data from 15/10/64 until 15/03/65 were employed. This constitutes part of the data base for the CIBSE "Example Weather Year" |26|. An intermittent heating cycle typical of UK practice was assumed (see Fig. 6). Figures 3 and 4 show the heating load profiles, for a city centre location, computed by the NBSLD program when it is sequentially modified by adding the WIND-CHT, ROOM-CHT on FLOW programs. The daily energy consumption (shown in Fig. 3) computed by the combined version (standard version of the NBSLD program with all three sub-models incorporated as additional subroutines) is 1.4% higher than the values computed by the standard version itself. Figure 4 shows the total energy consumption during the "whole" heating season computed by the different versions of the NBSLD program. The total energy consumption computed by the combined version is about 7% lower than the computations of the original version of the NBSLD program. However this "false" agreement does not reflect the accuracy of the standard version of the NBSLD program. It is simply due to a combination of errors in estimating the internal and external heat transfer coefficients and the air infiltrations rates (as shown in Fig. 4). These errors will not, in general, cancel each other out, and the original version of the NBSLD program cannot be regarded as universally reliable in this regard.

5. CONCLUSIONS

Intermediate-level sub-system models for convective heat transfer and air infiltration, of the type described in this work, appear to offer the best prospect for meeting the requirements of the new generation of dynamic building thermal models in terms of accuracy, economy and user friendliness.

Significant variations were detected in the computed results of the NBSLD program when assessing the individual effect of each of the intermediate-level sub-system models. However the simultaneous effect of all of them yielded only a small difference between the standard and modified versions of the NBSLD program in the case of the "test house" considered in the present study. This anomalous match arises from a fortuitous combination of inaccuracies in estimating the external and internal convective heat transfer coefficients and air infiltration rates.

6. ACKNOWLEDGEMENTS

The financial support provided by the National Council for Scientific and Technological Development of Brazil is acknowledged. The author also wishes to thank Dr. G.P. Hammond, for this invaluable guidance during this work, and Dr. F. Alamdari, for his help regarding the use of the ROOM-CHT program.

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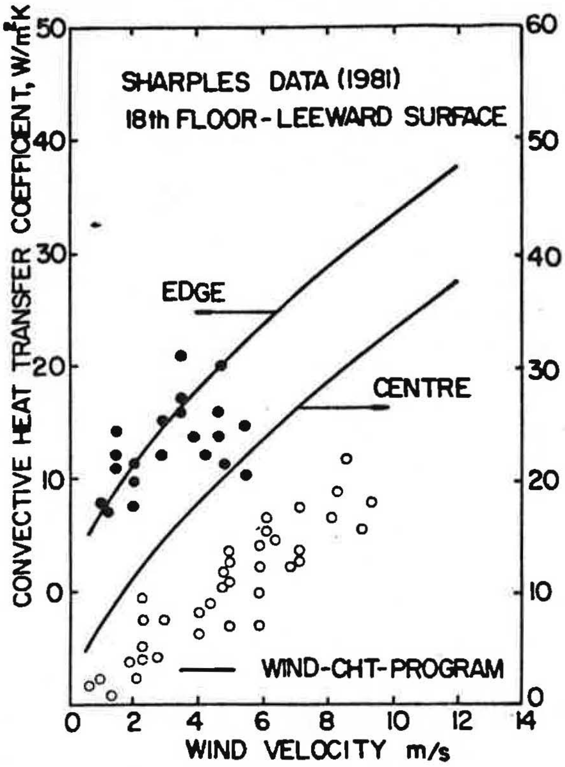

Fig. 1 - Comparison between the WIND-CHT program computations and Sharples' field measurements.

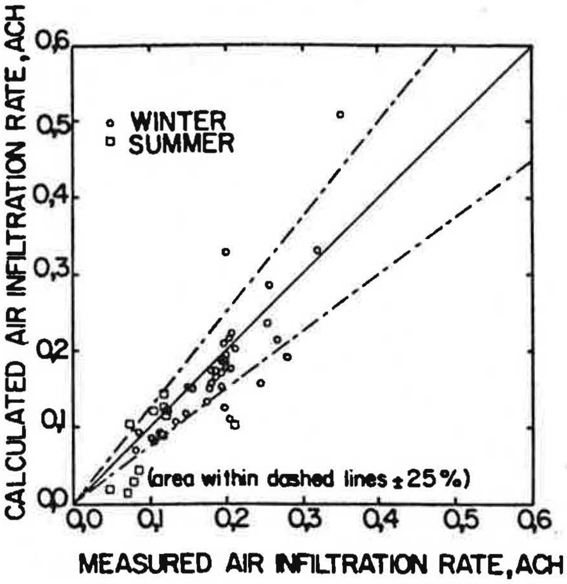

Fig. 2 - Measured air infiltration rates compared with the computations of the FLOW program.

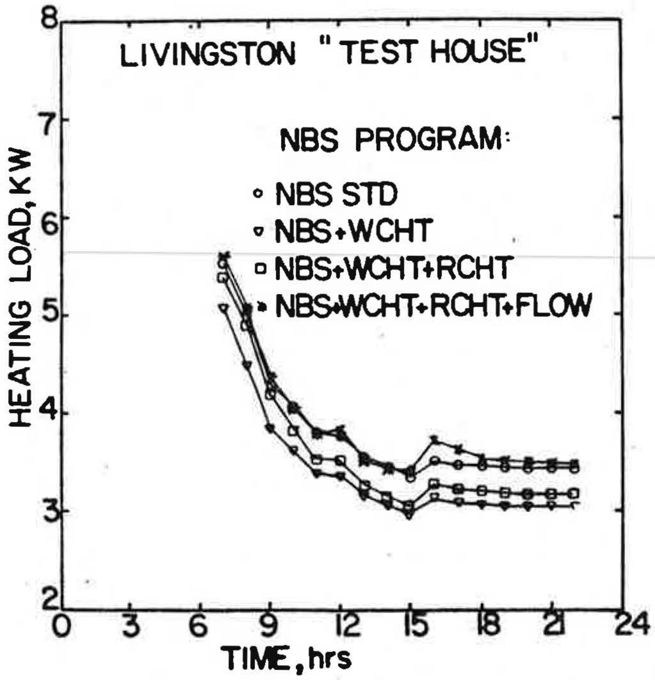

Fig. 3 - Influence of all three sub-system models on the NBSLD daily heating load.

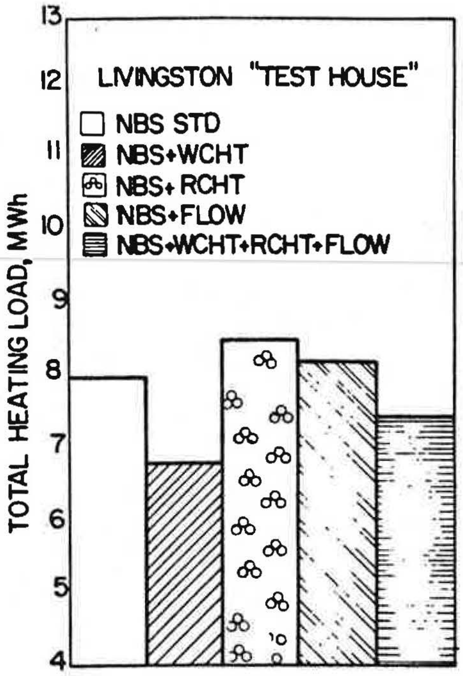

Fig. 4 - Total energy consumption during the "whole" heating season computed by the various versions of the NBSLD program.