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An Intermediate-level Model of External Convection for Building Energy Simulation

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SUMMARY

An 'intermediate-level' computer code for simulating convective heat exchange at the external facades of a building is described. The code is intermediate in complexity between the traditional data correlations found in guidebooks, and high-level air flow models based on techniques developed in the field of computational thermo-fluid dynamics. It takes into account most of the key dependent variables, including wind speed and direction, the change in shape and height of the atmospheric boundary layer over different terrains, and relative dimensions of the building. The computer is used to generalize available data correlations for the individual flow regimes that prevail around buildings, such as stagnation, boundary layer, and separated flows. Although external convection is normally wind-induced, the code also takes account of the influence of buoyancy-driven motion at low wind speeds. The computations of this improved model compare favorably with the albeit limited experimental data available for real buildings.

The improved external convection model has been incorporated as a subroutine in a building energy simulation code: the NBSLD (U.S. National Bureau of Standards Load Determination) program. Simulations were performed for two 'test houses' subject to U.K. and U.S. weather conditions respectively. The variation in the computed heating/cooling loads due to the replacement of the original external convection algorithm by the intermediate-level one is reported. These results form the basis for a discussion of the likely sensitivity of dynamic building thermal models to the treatment of external convection with regard to the simulation of both energy consumption and internal environmental conditions. Intermediate-level convection models are advocated as offering the best prospect for meeting the needs of building energy simulation programs in terms of accuracy, economy, and user-friendliness.

1. INTRODUCTION

1.1. The problem considered

In the aftermath of the 'oil crisis' of the early 1970s, energy conservation has become an important priority for industrialized countries. Carroll [1] recently analysed the energy consumption patterns in fifteen such countries (mainly from Western Europe and North America, but also including New Zealand and South Africa) over the period 1973 - 80. He noted that at least 40% of primary energy consumption in these nations could be attributed to energy use in buildings. The corresponding figure for the United Kingdom is 50% [2, 3], of which more than 60% is used to provide space conditioning and thermal comfort for occupants [2]. In order to assess the energy efficiency of new building designs, or evaluate the potential savings from alternative conservation measures for existing stock, it is necessary to accurately simulate the thermal performance

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of buildings. It is now widely recognized that to do this, traditional steady-state procedures must be replaced by ones which model the dynamic thermal response of the system [2, 4]. These dynamic models normally employ computational techniques in contrast to manual-calculation, steady-state methods. A range of modern approaches has been developed, including electrical network analogues, 'lumped-parameters' methods, and complex 'finite-difference' simulations [4]. However, a weakness in *all* these new approaches is that emphasis has been placed on simulating the transient thermal performance of the building fabric, while the air flow and convective heat exchange in and around the structure are modelled using only crude approximations. This was reiterated in the recent report of a validation study on the new generation of building thermal models by the International Energy Agency [5]. It concluded that the accuracy of such models is currently limited by uncertainties in their input data, particularly for air infiltration and convective heat transfer rates. An improved sub-system model for simulating external convection from buildings is described in the present work.

The rate of heat transfer between the exterior surfaces of a building and the surrounding environment is determined by a balance between the instantaneous heat gains and losses at the surface. In addition to wind-induced and buoyancy-driven convection, this interchange involves thermal radiation exchange with the surroundings, including solar radiation, and heat conduction through the building fabric. However, a comprehensive range of techniques is now available [4] for modelling these heat transfer mechanisms to within the accuracy of measured transport coefficients, such as surface emissivities and effective thermal conductivities. The calculation of convective heat transfer, on the other hand, involves a much less certain procedure of determining the surface-averaged convective heat transfer coefficient, h_c. This coefficient is defined by Newton's law of cooling:

$$q_c = h_c \Delta T \tag{1}$$

in terms of the wall (surface) convective heat flux, q_c, and the wall-to-external-air temperature difference, ΔT. h_c is sometimes combined with the corresponding radiative coefficient [6], h_r, to yield an external 'surface resistance' for each building element. For wind speeds $V > 3$ m s^{-1} typically, h_c is a function of the wind speed as well as the characteristic length of the surface, L, and the physical properties of the air. In the case of quiescent external conditions, $V < 0.75$ m s^{-1} typically, the convective motion is buoyancy-driven [7], and the temperature difference, ΔT, replaces the wind speed as the 'driving force' that determines the magnitude of h_c. The intervening regime, $0.75 < V < 3$ m s^{-1}, is characterized as 'mixed convection' in which the heat transfer coefficient is influenced by both the wind speed and temperature difference [8]. In order to facilitate data reduction and the use of scale models, it is usual to correlate experimental data for h_c in terms of dimensionless parameters. Dimensional analysis may be employed to show that for wind-induced convection the governing parameters are:

$$Nu(\equiv h_c L/K) = \phi_1(Re, Pr) \tag{2}$$

The molecular Prandtl number (Pr) for air is about 0.71 at 'normal' temperature and pressure. It is common practice to represent the Nusselt number relation by a 'power law' of the form:

$$Nu = C_1 Re^m Pr^n \tag{3}$$

where the exponent m depends on the nature of the flow and n is found to be about 1/3. The corresponding expressions for buoyancy-driven convection are:

$$Nu = \phi_2(Gr, Pr) \tag{4}$$

and, in terms of the Rayleigh number ($Ra \equiv Gr\,Pr$):

$$Nu = C_2 Ra^p \tag{5}$$

where the exponent p again depends on the type of flow [7].

1.2. Current practice

Most dynamic thermal simulation programs still evaluate wind-related heat exchange by employing surface-averaged heat transfer coefficients based either on the work of Jürges, as quoted by McAdams [9], or Rowley *et al.* [10]. Among the limitations in the equations proposed by these workers, are two especially relevant to building applications. The first limitation is that they are based on parallel flow experiments of a turbulent boundary layer, whereas the wind direction will, in general, not be parallel to the walls. The second is the absence of any dependence on surface length, which is contrary to the well-established fact that boundary-layer heat transfer coefficients are length-dependent. In view of these inadequacies, it is difficult to justify employing either Jürges' or Rowley's results for wind-related heat exchange calculations.

In an effort to obtain improved predictions, the ASHRAE Task Group on Energy Requirements [11] developed a simple algorithm for calculating the convective heat transfer coefficient, which is based on the field measurements of Ito *et al.* [12]. This algorithm has three advantages over the relationships derived from experiments and analysis of the turbulent boundary layer over flat plates [9, 10], but for which the h_c is presented as only a function of the wind velocity. Firstly, it is derived from full-scale measurements; secondly, it takes into account the relative position of the surface, and finally, it is based on the wind speed at 10 metres. The latter is the most widely documented wind speed parameter. This algorithm therefore has a much sounder physical basis than the relationships presented by either Jürges or Rowley. However, other influential parameters, such as the change in shape and height of the atmospheric boundary layer over different terrains, and the relative dimensions of the building, are not taken into account.

Melo [13] recently carried out an extensive survey of the literature up to 1985 on convective heat transfer relationships for building applications. He concluded that none of the existing experimental studies provide, by themselves, a reliable basis for determining exterior convective heat exchange from buildings.

1.3. The present contribution

In an attempt to produce improved methods for computing *internal* convective heat exchange, specifically in the case of warm-air-heated or mechanically-ventilated building spaces, the authors and their coworkers [14] developed a hierarchy of interacting and interdependent calculation methods. These ranged from 'lower-level' approaches, such as analytical solutions and data correlations, to the development of a 'high-level' flow model that solves the governing 'elliptic' equations for the room air flow [15]. Both the higher- and lower-level methods were then used to develop and verify an 'intermediate-level' computer code known as the ROOM-CHT (Room Convective Heat Transfer) program. The philosophy behind this approach is set out in the review by Alamdari, Hammond and Melo [14], where they argue that intermediate-level models appear to offer the best prospect for meeting the requirements of building energy simulation programs. These include the need to obtain a balance between accuracy, economy and user-friendliness.

The success of the above approach for internal convection led to the development of an analogous intermediate-level model for external convection from building; the WIND-CHT (Wind Convective Heat Transfer) program. An outline of this model was also given by Alamdari *et al.* [14] in order to illustrate the potential of such methods. The main purpose of the present contribution is to provide a detailed description of the model, including its mathematical content. In addition, comparisons will be made between the computations of the WIND-CHT program and the albeit rather limited, experimental data available from real buildings. Alamdari *et al.* [14] showed that intermediate-level models could be fairly readily incorporated into building energy simulation programs as subroutines. The capability of the present external convection model in this regard is demonstrated using a well-tested dynamic thermal model developed by the U.S. National Bureau of Standards (NBS) [16]. Simulations were performed on two 'test houses', under U.K. and U.S. weather conditions, and the sensitivity of the results to the replacement of the original external convection algorithm by the present one is assessed.

2. DEVELOPMENT OF THE WIND-CHT PROGRAM

2.1. The development process

The way that the intermediate-level model for external convection was developed is illustrated by the schematic diagram shown in Fig. 1. Here the blocks within the dashed line represent the iterative process of developing

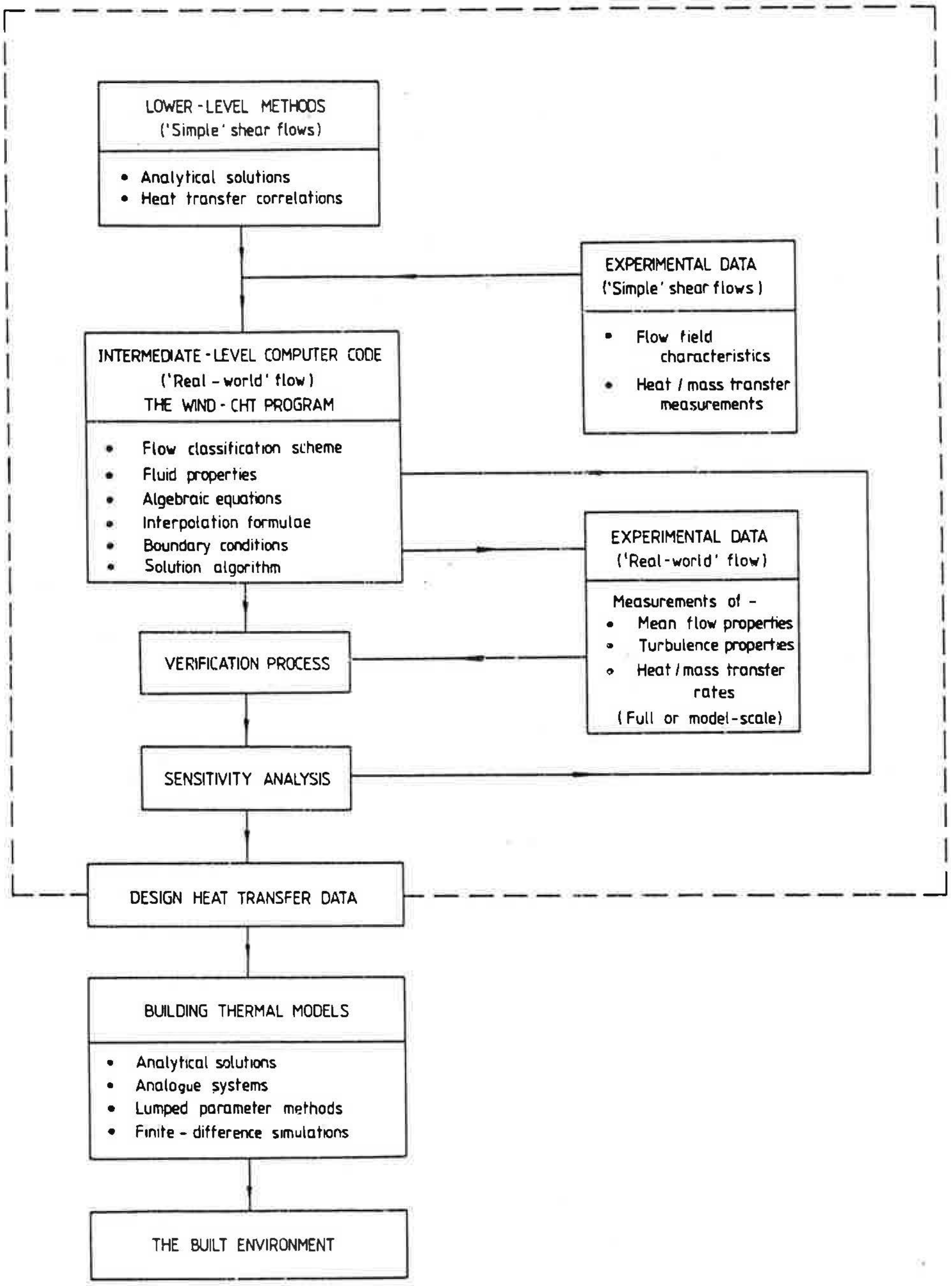

Fig. 1. Development sequence of the WIND-CHT program.

and verifying the model. Figure 1 has been adapted from a similar block diagram used by Alamdari *et al.* [14] to depict the general development sequence for intermediate-level calculation methods, which may include the use of higher-level computer codes as part of the verification process. In the case of the WIND-CHT program, experimental data were employed for validation purposes. The use of three categories or 'levels' for the various types of calculation methods is intended to reflect the potential generality of their range of application. Thus, analytical solutions and empirical data correlations, which are normally restricted to 'simple' shear flows, are regarded in the present context as 'lower-level' approaches. This categorization is not intended to disparage the use of the latter methods, which may still be appropriate for building applications other than external convection (see, for example, Alamdari and Hammond [7]).

In the development of intermediate-level models, the computer is used as a tool for generalizing the results of lower-level calculation methods [14]. Consequently, the former computer codes rely for their success on the latter, more traditional approaches.

The pattern of air flow around a building depends on the characteristics of the approaching wind, on the immediate surroundings, and on the size and shape of the structure itself. A building of even moderately complex shape may therefore generate flow patterns too complicated to generalize. (A fuller description of the air flow patterns around buildings is given by Melo [13]). Thus, in the present version of the WIND-CHT program, only flow patterns around buildings of simple rectangular cross-section are considered.

The WIND-CHT program utilizes the capabilities of the computer to generalize data correlations for the individual flow regimes that prevail around buildings. In the case of a rectangular structure facing the prevailing wind, these regimes would include stagnation flow on the windward facade, boundary-layer flow over the flat roof and side-walls, and separated flow on the leeward facade. When the wind strikes the building obliquely, various 'combined flow' regimes will be generated on the surfaces. Thus, the predominately windward surface would experience both stagnation and boundary-layer flows, while a similar combination would occur on the remaining exposed surfaces of the structure.

2.2. *The verification process*

The WIND-CHT program has been verified using experimental data, obtained from full- and model-scale tests. This procedure was conceived as an iterative (or feedback) process, as implied by the block diagram in Fig. 1, from which *ad hoc* corrections to the intermediate-level code would be made where necessary. This proved to be needed in the present case, when it was found that laboratory-scale data correlations did not correspond to full-scale building heat transfer measurements on windward facades.

The correlating equations employed in the WIND-CHT program for individual flow regimes were derived from data for smooth surfaces. In the case of the windward facade, a new correlation was developed from field measurements on full-scale, glass-fronted office blocks. Consequently, the present model is essentially applicable to buildings having large glazed areas. Nevertheless, in modern architectural design, window heat exchange takes on an increasingly important role in the overall building balance as thermal insulation standards improve [17]. In any case, the enthusiasm among architects for the inclusion of passive solar design features leads to an increased proportion of glazed surfaces. Rough surfaces will yield rather higher heat transfer coefficients than those computed using the WIND-CHT program. However, there is little agreement in the literature as to the extent of this enhancement due to exterior cladding materials.

The last stage in the verification process for intermediate-level convection models (see Fig. 1) is to test their sensitivity to changes in key input parameters. The latter will only be known within an 'uncertainty' band. If a modest change in parameter results in a more-than-proportional change in the output heat transfer coefficient, then the value assigned to the variable must be refined, or its uncertainty band reduced.

3. WIND AND ITS SIMULATION

The atmospheric boundary layer is the lower region of the atmosphere from which momentum is extracted in order to compensate for the shear stress at the earth's surface. The wind developed in this region varies widely in structure because of strong dependence upon topography, surface roughness features and the possible occurrence of thermal stratification. Above the layer of influence by surface shear stress, the air moves purely under the influence of pressure gradients, which are caused by the differential heating of the earth's surface by the sun, and attains what is known as the gradient velocity, V_g. The height at which the gradient velocity is attained will be denoted by Z_g, and is generally of the order of 300 - 600 m.

Several formulae have been suggested to describe the variation of the wind velocity with height [18]. One of them is the bilogarithmic profile obtained by utilizing simple near-wall scaling arguments applied to a flat-plate turbulent boundary layer. However, Davenport [19] has noted that, although the 'logarithmic law' agrees well with measurements over natural surfaces of roughness varying between smooth mud flats, water and thick grass, it has not been demonstrated experimentally to be representative of urban areas. Thus, the reliability of the log law in providing a numerical simulation of the wind speed profile does not appear to be greater than that for the simple power-law profile given by:

$$V_z/V_g = (Z/Z_g)^{\alpha} \quad (6)$$

where α is a constant which depends on the roughness of the ground. To determine values of α and Z_g for different surfaces, Davenport [19] collected together mean wind profile data for a wide range of countries and terrains, and suggested the representative values displayed graphically in Fig. 2. The profiles

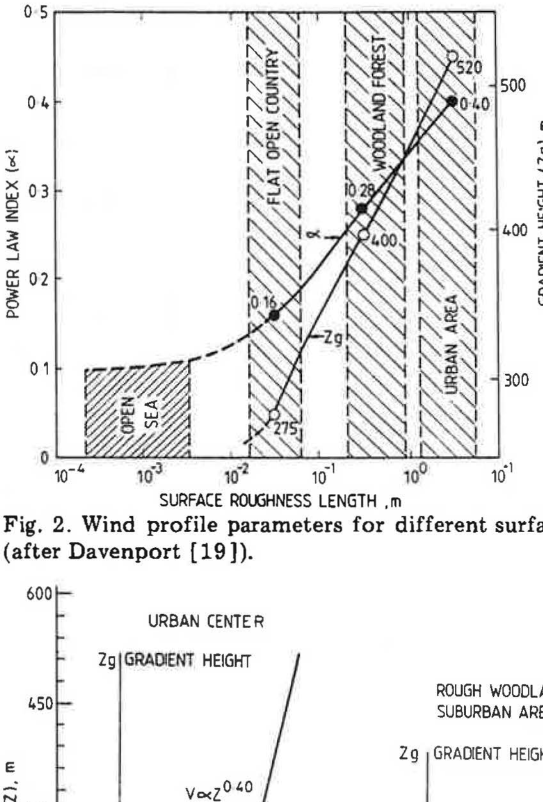

Fig. 2. Wind profile parameters for different surfaces (after Davenport [19]).

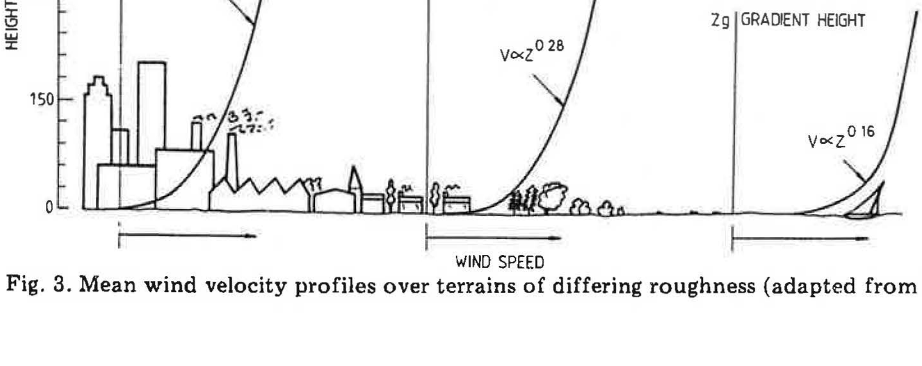

Fig. 3. Mean wind velocity profiles over terrains of differing roughness (adapted from Davenport [19]).

for three types of terrain — open country, a suburban area and an urban center — are shown in Fig. 3.

4. ELEMENTS OF THE WIND-CHT PROGRAM

There are two main elements of the present model: the treatment of the wind profile and the associated choice of velocity scale, and the convection relations employed for the different surfaces of the building. The wind profile is computed using a power-law expression, eqn. (6), in which the index is varied with the local topography. Three shapes are adopted to represent typical terrains [14] corresponding to those illustrated in Fig. 3. Davenport's values [19] for the related power-law index, α, and gradient height, Z_g as depicted in Fig. 2, are utilized. The other features of the WIND-CHT program are indicated below.

4.1. Choice of velocity scale

Meteorological measurements are usually made in open terrain (e.g., at airports), while residential buildings are more commonly located in sheltered areas. The wind speed must therefore be adjusted to take into account the fact that the wind profile changes in accordance with the type of terrain. Assuming that the gradient velocity, V_g, is independent of the terrain type, the wind speed at the desired site can be calculated by the following relationship [13]:

$$V_z = (Z_g'/Z')^{\alpha'} (Z/Z_g)^{\alpha} V_z' \quad (7)$$

where the unprimed quantities refer to the desired site and the primed quantities refer to the wind measurement site.

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 the buildings 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. Thus,

$$V_{av} = \int_{Z_1}^{Z_2} V\, dZ \Big/ \int_{Z_1}^{Z_2} dZ \tag{8}$$

where Z_1 and Z_2 are the lower and upper elevation respectively of the floor under consideration. Substituting eqn. (7) into eqn. (8) and integrating, yields:

$$V_{av} = V_g \{(Z_2^{\alpha+1} - Z_1^{\alpha+1})/ [Z_g^{\alpha}(\alpha+1)(Z_2 - Z_1)]\} \tag{9}$$

4.2. Convective heat transfer correlating equations

The current approach to modelling external convection is based on the separate treatment of the flow regime and associated heat transfer over each surface of the building. Five regimes are considered: (a) boundary-layer flow; (b) completely separated flow; (c) stagnation flow; (d) buoyancy-driven convection; and (e) combined flow. In each case the *surface-averaged* Nusselt number is computed, with the fluid properties for air evaluated at the so-called 'film temperature' [7] (the arithmetic mean of the surface and surrounding air temperatures).

(a) Boundary-layer flow

This type of flow prevails over the flat roof and side-walls of the building when it faces the prevailing wind. In order to obtain an expression valid over the full range of laminar, transitional and turbulent flow, the interpolation formula of Churchill and Usagi [20] was used in a similar manner to that recently employed by Alamdari and Hammond [7] for buoyancy-driven convection. If the Prandtl number is taken to be 0.71, then the extended correlating equation has the form:

$$Nu_p = [(0.59Re^{1/2})^6 + (0.032Re^{4/5} - 745)^6]^{1/6} \tag{10}$$

where 'standard' correlations [13] have been adopted for the asymptotic laminar and turbulent states. The length scale, L, used in this case is the surface length in the streamwise direction. Equation (10) is valid for $Re > 2.86 \times 10^5$, and below this value only the first, laminar flow part of the expression is employed. However, due to the relatively large dimensions of buildings, laminar flow will only occur at very low wind speeds ($V < 0.5$ m s^{-1}).

(b) Completely separated flow

The free-stream turbulence intensity has little effect upon heat transfer in the separated flow region at the rear of a bluff body, and consequently the convective heat transfer is practically constant in the lee of the building [13]. The Nusselt number dependence is therefore satisfactorily correlated by Sogin's relationship [21]:

$$Nu_s = 0.20\, Re^{2/3} \tag{11}$$

Here the length scale is computed from [7]:

$$L = 4A/P \tag{12}$$

where A is the surface area and P its perimeter. This is analogous to the concept of the 'hydraulic diameter' widely used in fluid mechanics.

(c) Stagnation flow

Unfortunately, laboratory-scale correlations for the stagnation flow, such as that proposed by Sparrow *et al.* [22], were found to be unrepresentative of the albeit very limited, field measurements [14]. This is probably due to the combined influence of high wind turbulence intensity, and building/ground interaction effects. Thus, a new power-law correlation was developed by Melo [13] from the field measurements on office buildings by Ito *et al.* [12] and by Sharples [23]. These data sets display a wider variation between themselves than would have been desired, but they are the only suitable measurements available. This correlation has the following form,

$$Nu_{st} = 0.14Re^{0.69} \tag{13}$$

Equation (12) is again employed to compute the length scale.

(d) Buoyancy-driven convection flow

Improved data correlations for buoyancy-driven convection from buildings surfaces have been derived by Alamdari and Hammond [7]. These correlating equations provide a smooth fit to data across the full range of laminar, transitional and turbulent air flows, in contrast to the 'standard' two-part model. These improved data correlations for vertical and horizontal surfaces respectively are:

$$Nu_b = [(0.58Ra^{1/4})^6 + (0.11Ra^{1/3})^6]^{1/6} \qquad (14)$$

and

$$Nu_b = [(0.54Ra^{1/4})^6 + (0.14Ra^{1/3})^6]^{1/6} \qquad (15)$$

Although the coefficients in these two relations appear similar, it should be noted that their length scales differ. In the former case the height of the wall is used, while eqn. (12) is adopted for the latter.

(e) Combined flow

The final component of the WIND-CHT program is the weighting function used to interpolate convection coefficients when the wind direction is non-orthogonal to the building surfaces. The approach adopted was to combine the relevant correlation in such a way that the limiting conditions are satisfied. Thus, when the angle of attack relative to the oncoming flow (θ) is equal to zero, only the stagnation or separated flow correlation was employed. Conversely, when θ is equal to 90°, only the parallel flow was considered. When θ lay between 0 and 90°, an interpolation between the two limiting conditions is employed. A simple cosine squared relation was then adopted for the weighting function [14], as this gave a plausible variation between the various combinations of the pure flows, in the absence of reliable field measurements. This has the form:

$$Nu_f = \cos^2\theta Nu_{s/st} + (1 - \cos^2\theta) Nu_p \qquad (16)$$

Finally, in accordance with the recommendation of Siebers *et al.* [8], a geometric mean of the buoyancy-driven and forced convective heat transfer coefficient is employed when mixed convection prevailed, i.e.,

$$Nu = (Nu_f^3 + Nu_b^3)^{1/3} \qquad (17)$$

An isometric view of the convective heat transfer coefficient computed by the WIND-CHT program is shown in Fig. 4 as a function of the wind velocity and angle of attack. The computations were performed for a vertical windward surface (5 m × 3 m high) at ground level, and located in an urban area. The wind velocity used for this and all subsequent figures has been scaled to that at the 'standard' height of 10 m above the ground. Figure 4 illustrates, quite dramatically, the ability of the present intermediate-level model to account for wind speed and direction. It also shows that the former has generally a much large effect than the latter.

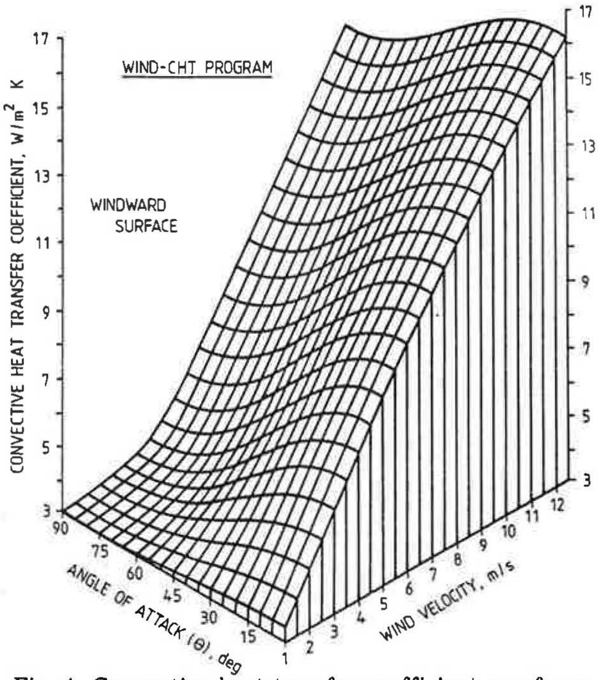

Fig. 4. Convective heat transfer coefficient as a function of wind velocity and angle of attack.

5. COMPARISONS WITH FIELD MEASUREMENT DATA

Some capabilities of the WIND-CHT program are demonstrated by Fig. 5, where its computations for the leeward facade of the city-centre, multi-storey Arts Building at Sheffield University, U.K., are compared with Sharples' data [23]. These results are intended to be only illustrative, and the corresponding ones for the windward facade are given by Alamdari *et al.* [14]. Further detailed comparisons with Sharples' data are also reported in Melo's thesis [13]. The WIND-CHT program yields only the surfaced-averaged heat transfer coefficient on the facade, which in the case of the Arts Tower

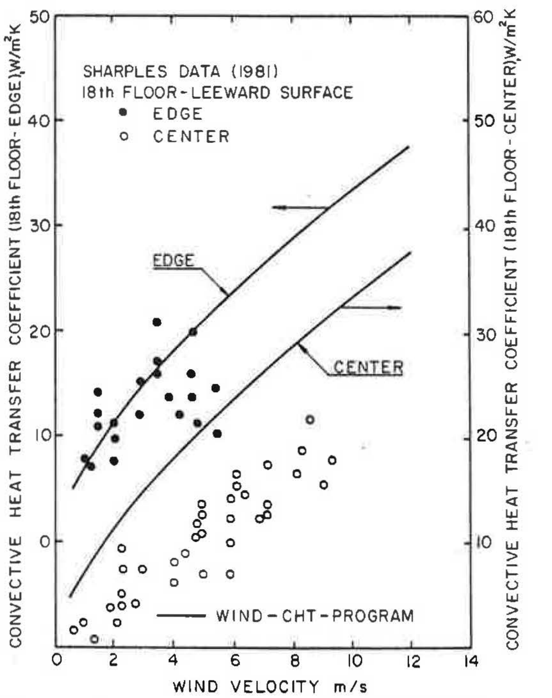

Fig. 5. Comparison between the WIND-CHT program computations and Sharples' field measurements.

is 36 m 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. It should be noted that Sharples' measurements are typically 100% lower [13, 14] than those of Ito *et al.* [12], obtained from a six-storey office building in Tokyo.

A comparison between the WIND-CHT program computations and the data correlations recommended in the CIBSE Guide [6] and by the ASHRAE Task Group [11] are shown in Fig. 6. The experimental data set is a combination of measurements obtained by Sharples [23] at the edge and in the middle of the leeward test facade. These comparisons demonstrate the ability of the WIND-CHT code to account for the influence of building height relative to that of the atmospheric boundary layer. Unfortunately, the field measurements necessary to illustrate its capabilities for simulating the effect of wind direction upon the heat transfer from individual surfaces of a building are currently not available.

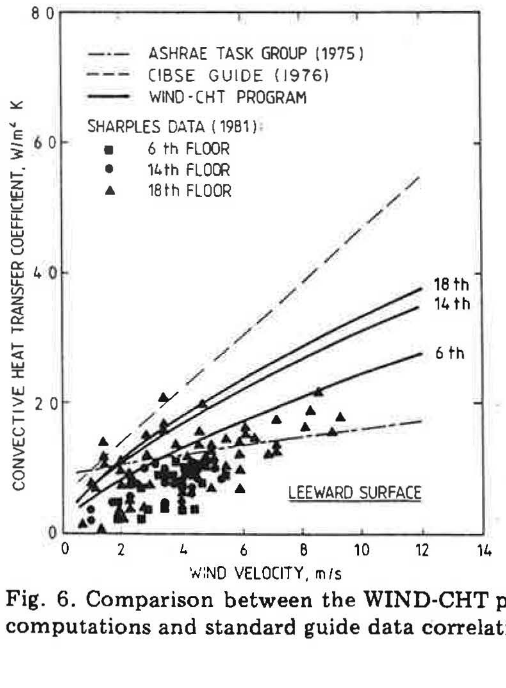

Fig. 6. Comparison between the WIND-CHT program computations and standard guide data correlations.

6. COMPARATIVE ANALYSIS ON THE NBSLD PROGRAM

In the context of the present work, it was felt desirable to quantify the influence of input values for external convective heat transfer coefficients on the predicted heating/cooling load within typical domestic dwellings. The NBSLD program [16], which is one of the most sophisticated dynamic building thermal models, was chosen for this purpose mainly for two reasons: firstly, because of the previous experience of one of the authors in its use [24], and secondly, because it was well documented. A comparative assessment of the simulated building energy performance of two 'test houses', under differing weather conditions, was obtained by replacing the original external convection subroutine in the NBSLD code with the WIND-CHT program. This provides an indication of the likely sensitivity of building thermal models to changes in exterior heat transfer coefficients.

In the NBSLD program the outside surface temperatures, at a given time t, are calculated by solving a heat balance equation at each external surface of a building. Two components of such a heat balance equation are of special interest to this study; the convective heat transfer from the surface to the ambient air and the radiative heat transfer emitted by the surface. In the original version of the NBSLD program, these two components are reduced to only one by employing the combined radiative and convective film coefficient obtained by Rowley *et al.* [10]. In the new version, which will generally hereafter be referred to as NBSWIND, the convective coefficients are calculated by employing the WIND-CHT program which was incorporated as an additional subroutine into the NBSLD code. In order to replace Rowley's coefficients, it was necessary to combine the convective heat transfer coefficients with an appropriate radiative heat transfer coefficient, h_r. This was calculated via the Stefan–Boltzmann 'law' [13], assuming an exterior surface emissivity of 0.9 and a shape factor of unity.

A comparative analysis on the NBSLD program under winter conditions was performed using 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]. Full details of the construction and thermal properties of this test house are given by Melo [13]. The computations reported here represent the normal, 'thermally massive' construction of such dwellings, although Melo [13] also presents corresponding results for a more lightweight structure. In order to simulate the heating load for the 'test house' on a typical winter day, meteorological data for Kew, London (51°28′N, 0°19′W), on December 21, 1964, were employed. This constitutes part of the data base for the CIBSE (U.K. Chartered Institution of Building Services Engineers) 'Example Weather Year' [26]. Where the calculations were performed for the 'whole' heating season, meteorological data from October 15, 1964, until March 15, 1965, were employed. An intermittent heating cycle, typical of U.K. practice, was also assumed.

A comparison between the convective heat transfer coefficients, computed using the standard version of the NBSLD program, and those for the WIND-CHT program is shown in Fig. 7. The latter relates to the Livingston 'test house' with three different kinds of terrain. The NBSLD program values were calculated in accordance with Rowley's equation [10], but with the values shown here reduced by 4 W/m^2 K to allow for the effect of radiative exchange [13]. The WIND-CHT program values represent an area-weighted average for all surfaces and for all wind directions.

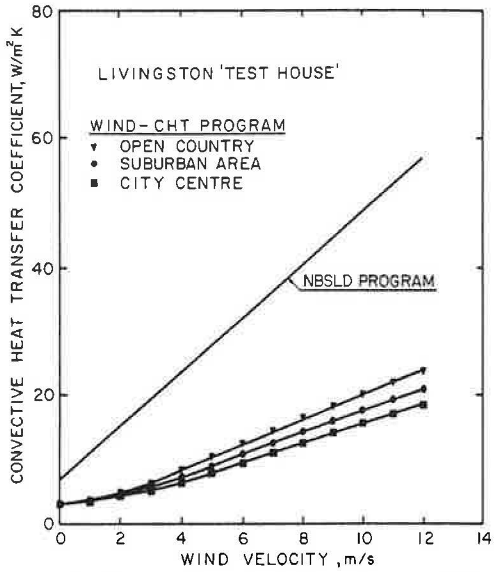

Fig. 7. Convective heat transfer coefficients computed by the NBSLD and WIND-CHT programs.

In order to represent summer conditions requiring air-conditioning, the Houston test house was simulated using all the operational and climatic data given by Kusuda [16]. This is a real test facility located in Houston, Texas, U.S.A. (29°4′N, 95°24′W) and the weather data used were those measured on September 3, 1977. In the simulations reported below, the results for the summer cooling of this house are presented in closed brackets, while those for winter heating in the Livingston 'test house' are not.

The heating (cooling) load profiles computed by the standard version of the NBSLD program, together with those using the NBSWIND program, are shown in Figs. 8 and 9 respectively. The former also gives an indication of the control cycle used for the intermittent heating system in the Livingston house. The daily energy consumption computed by the standard program was 61 (72) kWh, and this decreased (increased) by 10% (7%) when the NBSWIND code was used. These computations required central processor times on a DEC VAX 11/782 computer of 58 (23) and 60 (24) seconds for the standard and revised versions of the NBSLD program respectively. The corresponding heating load profiles reported by Alamdari *et al.* [14] were found to be incor-

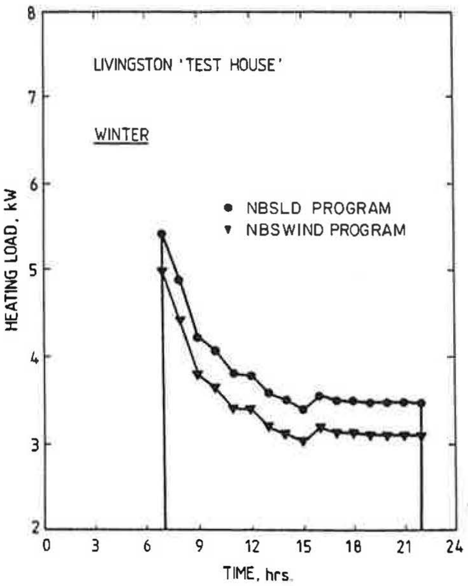

Fig. 8. Daily heating load computed by the NBSLD and NBSWIND programs.

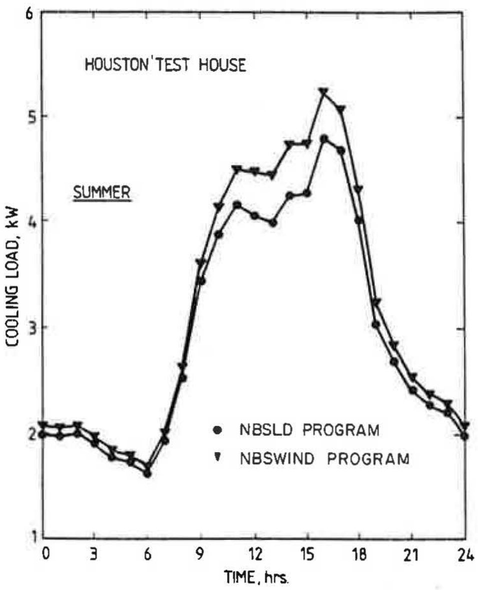

Fig. 9. Daily cooling load computed by the NBSLD and NBSWIND programs.

rect, due to a coding error discussed by Melo [13]. These earlier results indicated a 23% *increase* in the heating load, in contrast to the present fall of 10% when the WIND-CHT program was employed.

The monthly total heating energy consumption for the Livingston test house, calculated using the two different versions of the NBSLD program, is shown in Table 1. Here it can be seen that NBSWIND yields values that are some 15% lower than those of the standard

TABLE 1

Month	Energy consumption (MWh)	
	NBSLD	NBSWIND
October	547.8	413.1
November	1211.6	1028.2
December	1860.9	1646.7
January	1884.7	1651.0
February	1663.7	1419.5
March	821.6	655.1
Total	7990.2	6813.6

version of the program. The latter employs values for the combined external heat transfer coefficients always higher than the values computed via the WIND-CHT program under comparable environmental conditions. This accounts for the difference in both the computed heating and cooling loads. When the combined external heat transfer coefficients are decreased, the heat balances at the exterior surfaces of a building are modified in such a way that the heat released by the combined action of radiation and convection to the surrounding air becomes smaller and, consequently, the temperatures of the external surfaces become higher. This increases the cooling load and decreases the heating load. However, Allen and Whittle [27] have recently argued that the main influence of external convection may derive from the variations in exterior surface temperatures themselves, which can ultimately cause significant changes in internal zone temperatures. Such effects may therefore be more significant for environmental modelling in the case of modern domestic building, than for the computation of their overall energy budget.

7. CONCLUDING REMARKS

An 'intermediate-level' model for convective heat exchange from the exterior surfaces of buildings has been developed. The wind profile is simulated using a power-law expression in which the index depends on the local topography. An integral velocity scale over the area of building surface of interest is computed from this profile in order to obtain the appropriate Reynolds number. The heat transfer correlating equations chosen for these surfaces depend on the prevailing flow regimes, which are taken to be various combinations of stagnation, boundary-layer, separated, or buoyancy-driven flow. A simple cosine squared function is employed to ensure a plausible variation between the 'pure' wind-driven flows, when the wind direction is non-orthogonal to the building surfaces.

The present version of the external convection model, the WIND-CHT program, has been derived from data for smooth surfaces. This means that it is particularly suited to computing surface heat transfer over windows. Here the exterior coefficient accounts for some 30% of the total glazing thermal resistance [27]. Another potential limitation of the model arises because it is based on flow patterns that are encountered around buildings of rectangular cross-section. However, neither this, nor the surface texture restriction, place serious limits on the model's use. In any case, the structure of the model is such that it can be readily extended as better data become available.

The present model is 'intermediate' in the sense of falling between traditional approaches [11, 16], which involve simple data correlations for the external convection coefficient dependent only on wind speed, and high-level air flow models [15] that solve discretized versions of the governing partial differential equations for the whole flow field. Although the latter are potentially more general and accurate, the authors and their coworkers previously noted [14, 15] that they employ computational resources of the same order as the new generation of dynamic building energy simulation programs. Consequently, it would not be appropriate to directly couple such computer codes together as any gain in terms of accuracy, over lower- and intermediate-level methods, would be far outweighed by the extra resources consumed. Alamdari *et al.* [14] therefore argued that intermediate-level convection models offer the best prospect of meeting the requirements of modern building thermal models by providing a realistic balance between accuracy, economy, and user-friendliness.

It has been demonstrated here that the WIND-CHT program is capable of being readily incorporated as a subroutine into building thermal models — the NBSLD program in the present case. In this mode, the external convection model responds very rapidly to changes in climatic conditions simulated by a weather file or tape. This is because the time-scale for convective transport is very short compared with that for heat conduction through the building fabric. In practice, energy simulation programs normally employ hourly time steps, and therefore this dynamic response characteristic of the external model is less significant. Nevertheless, the comparative analysis of the NBSLD program, with and without the WIND-CHT program, did provide a means of assessing the likely sensitivity of building thermal models to the treatment of external convection. In the case of the two 'test houses' employed here, a change of about 7 - 15% in the computed energy consumption was observed. However, the sensitivity to external convection will, in general, depend on the nature of the building energy simulation program being used, and on the conditions prevailing in and around the simulated buildings. Indeed, so-called 'passive solar' buildings, with a high proportion of glazing on the sun-facing facade, are likely to be more sensitive to the external convection modelling than the 'conventional' houses simulated here. This applies as much to the effect on internal environmental conditions in rooms adjoining this facade as to the overall energy budget of the building.

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LIST OF SYMBOLS

A	area of heat transfer surface (m^2)
c_p	fluid specific heat at constant pressure (J/kg K)
g	gravitational acceleration (m/s^2)
Gr	Grashof number [$\equiv \rho^2 g\beta\Delta TL^3/\mu^2$]
h_c	surface-averaged convective heat transfer coefficient (W/m^2 K)
h_r	surface-averaged radiative heat transfer coefficient (W/m^2 K)
K	fluid thermal conductivity (W/m K)
L	characteristic length of heat transfer surface (m)
Nu	Nusselt number [$\equiv h_cL/K$]
p	perimeter of heat transfer surface (m)
Pr	Prandtl number [$\equiv c_p\mu/K$]
q_c	surface-averaged convective heat flux (W/m^2)
Ra	Rayleigh number [$\equiv Gr\,Pr$]
Re	Reynolds number [$\equiv \rho V_{av}L/\mu$]
T_a	temperature of the quiescent (ambient) air (K)
T_w	'wall' (surface) temperature (K)
V	wind velocity (m/s)
V_{av}	average wind velocity over the area of building (heat transfer) surface of interest (m/s)
V_g	gradient velocity of the wind (m/s)
Z	height above ground level (m)
Z_g	height at which the gradient velocity is attained (m)
Z_1	lower elevation of the floor (storey) of interest (m)
Z_2	upper elevation of the floor (storey) of interest (m)
α	power-law index
β	coefficient of volumetric expansion (K^{-1})
ΔT	[$\equiv T_w - T_a$] (K)
θ	angle of attack between the approaching (oncoming) wind and the normal to the windward surface (°)
μ	fluid dynamic viscosity (kg/ms)
ρ	fluid density (kg/m^3)

Subscripts

b	buoyancy-driven flow
f	forced convection flow
p	parallel flow
s	separated flow
st	stagnation flow
z	property at height z above ground level

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