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MODELLING BUILDING AIRFLOW AND RELATED PHENOMENA*

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SUMMARY

A hierarchy of calculation methods are currently being used to determine airflow and related phenomena, such as convective heat exchange and smoke movement, in the context of the built environment. These range from low-level (or 'short-cut') methods through intermediate-level (or 'zonal') models to high-level (or 'field') computer codes. The strengths and weaknesses associated with each approach are outlined by reference to the methods developed by the author and his co-workers for modelling convective heat transfer in and around buildings. In the light of the current state-of-the-art, future action areas are suggested for the BEPAC 'Air Movement' Task Group.

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1. Introduction

There is currently an upsurge of interest in air movement and stratification within the technical community concerned with building energy and environmental performance. This is not surprising in view of the growing awareness of the importance of modelling building airflow and related phenomena for performance analysis. A number of sophisticated building energy simulation programs have been developed since the mid-1970's that model the dynamic thermal behaviour of the system. However, a weakness in all these new computational approaches is that emphasis has been placed on simulating the transient performance of the building fabric, while air flow and convective heat exchange in and around the structure are modelled using only rough approximations. Furthermore, considerations of environmental quality within building spaces, which is again heavily dependent on air movement, have taken on a high profile in recent years. In addition, the adoption of some of the modern architectural features, such as atria in office complexes, gives rise to new and complex fluid dynamic problems.

It is hoped that computational fluid dynamics (CFD) modelling may eventually replace, or at least complement, the more traditional approaches to simulating building airflow. All thermo-fluid problems are governed by so-called 'conservation laws' such as those for mass, momentum, thermal energy, and species concentration. Each of these may be represented by an equation of the form (see Alamdari, Hammond & Mohammad, 1986):

$$\underbrace{\frac{\partial}{\partial x_j}(\rho u_j \phi)}_{\text{CONVECTION}} = \underbrace{\frac{\partial}{\partial x_j}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_j}\right)}_{\text{DIFFUSION}} + \underbrace{S_\phi}_{\text{SOURCES OR SINKS}}$$

In principle it is therefore possible to solve such elliptic partial-differential equations for any conservation phenomenon using modern numerical techniques. This includes air, heat and smoke (or other contaminant) transport within and between the zones of naturally and mechanically-ventilated buildings. However, in practice, high-level CFD computer codes presently have a number of limitations (outlined in Section 5 below), and are costly in terms of computing resources. Consequently, simplified methods are often used, and are likely to be so for some time to come.

In the present contribution, an attempt is made to categorise the range of thermo-fluid calculation methods that are used in connection with building energy and environmental analysis. An example of each type is taken from those developed by the author and his co-workers for determining convective heat transfer in and around buildings. These are used to illustrate both the strengths and weaknesses of models in the different categories. This leads naturally to suggestions for future action areas that could be addressed by the BEPAC 'Air Movement' Task Group.

2. Classification of Thermo-fluid Calculation Methods

Thermo-fluid models may be usefully divided into a number of simplified categories as indicated below:

(i) 'Lower-level' or 'short-cut' methods : these are analytical solutions and empirical data correlations that apply to a very narrow class of flows or range of conditions. Examples of this category include air change rate and regression techniques used to determine air infiltration (reviewed by Liddament, 1986), as well as the sort of 'back-of-the-envelope' calculations employed to estimate smoke movement and fire spread like those recently incorporated into the software package called ASK FRS by the Fire Research Station (Cox, 1987).

(ii) 'Higher-level' or 'field' methods : these involve the solution of the governing conservation equations for the flow and thermal field (derived from the Navier-Stokes equations). In their most general form such methods are potentially capable of handling complex time-dependent, three-dimensional, turbulent flows. They require a sophisticated numerical solution procedure and associated turbulence modelling. Examples of the application of this type of model are the simulation of wind flow over 'two-dimensional' buildings by Hanson, Summers and Wilson (1984), and of smoke movement and fire spread within buildings by Cox and Kumar (1983).

(iii) 'Intermediate-level' or 'zonal' methods : these are computer-based methods incorporating the results of analytical and/or experimental observations to prescribe the flow and thermal field. They are in principle problem-specific and, as the name implies, they are intermediate in complexity between the other two types of model. However, a particular code may be capable of application to quite a wide range of conditions. An example of models in this category would be the mass balance/flow network approach that has been used to determine both air infiltration (Liddament, 1986) and smoke movement (Irving, 1979) in multi-zone buildings.

The author and his co-workers (see, for example, Alamdari, Hammond and Melo, 1984) have also developed a hierarchy of interacting and interdependent calculation methods like those above in order to compute convective heat exchange for the purposes of building energy simulation. In this case, it was found the intermediate-level models were often the most appropriate for providing a suitable balance between accuracy, economy, and user-friendliness. The interrelationship between the various calculation methods is illustrated by the schematic diagram shown in Figure 1. The classification scheme adopted for different 'levels' was intended to reflect the potential generality of their range of application, rather than their scientific sophistication. The iterative process of developing and verifying intermediate-level methods is represented in Figure 1 by the blocks within the dashed line. Both experimental data, obtained from full and model-scale tests, and the computed results of a higher-level thermo-fluid computer code have been used for verification purposes. This was conceived as a feedback process from which ad hoc corrections would be made to intermediate-level computer codes where necessary. In the following three sections, some of the methods devised at Cranfield are used to illustrate the strengths and weaknesses of each category of model. The author has chosen to discuss his own work for this purpose simply because it would be invidious to criticise here models developed by others.

3. Lower-level Methods

In order to illustrate the potential of short-cut methods, the improved correlating equations developed by Alamdari and Hammond (1983) for calculating buoyancy-driven convection from isolated surfaces will be considered. These are more elaborate than earlier, 'standard' data correlations, but cover the full range of laminar,

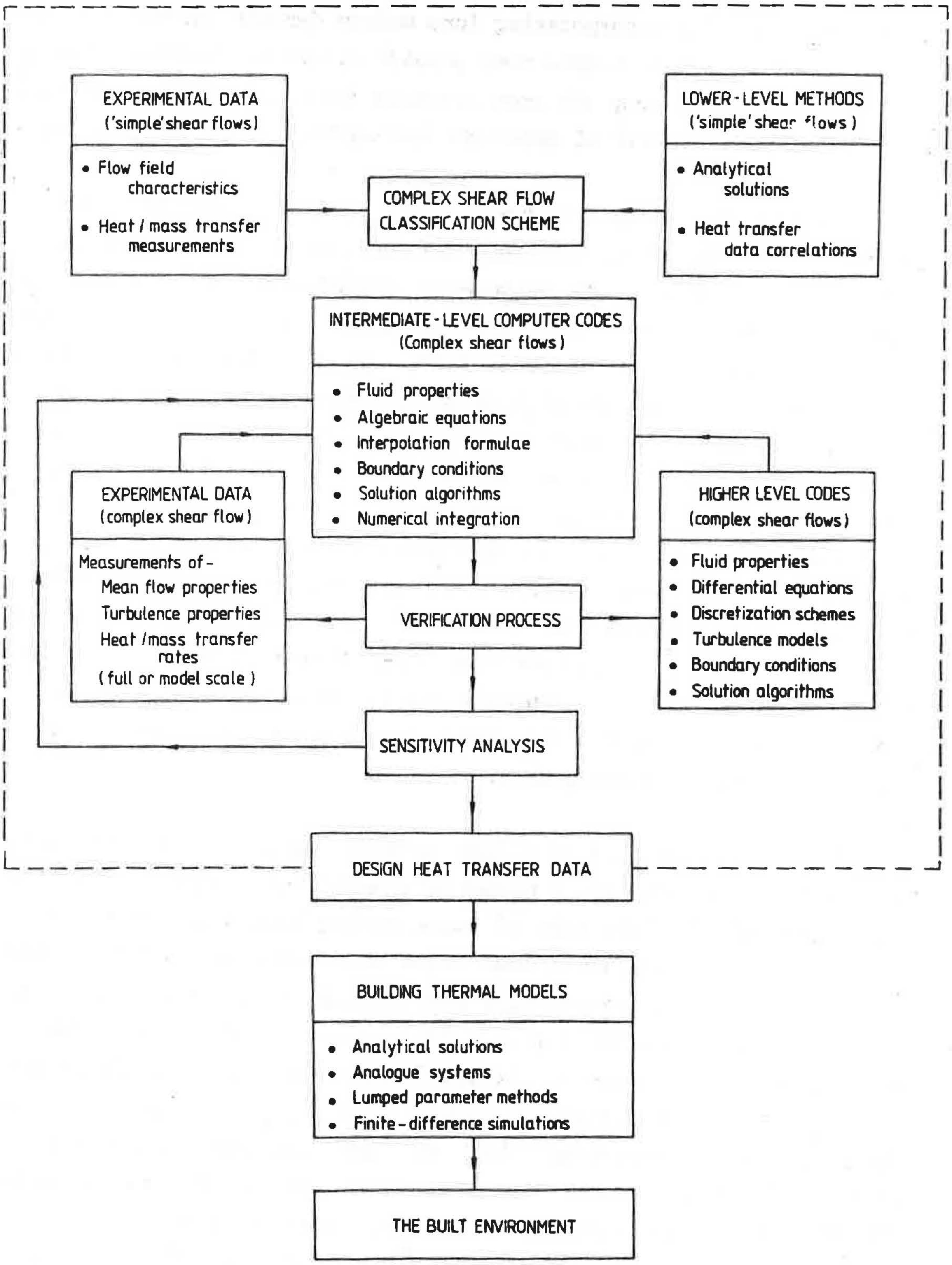


Fig. 1. Interrelationship Between the Various Calculation Methods for Building Convective Heat Transfer (after Alamdari, Hammond and Melo, 1984)

transitional and turbulent airflows. They were presented in a convenient form for incorporating into modern dynamic thermal models. Subsequently they have become very popular within the building energy simulation field as they are more accurate than earlier correlations, and also reduce the risk of numerical instability in thermal models.

Alamdari and Hammond's correlating equations for the Nusselt number, or dimensionless (surface-averaged) convection coefficient, were initially derived as relatively complicated functions of the Rayleigh number. These were found to compare favourably with recent experimental data for isolated surfaces. In the context of the build environment, where the thermo-physical properties of air do not very greatly, the convective heat transfer coefficient (h_c) was recovered in dimensional form. This was shown to be, in general, dependent on the surface-to-air temperature difference (ΔT) and characteristic length of the surface (L). The consequent variation for both vertical and horizontal surfaces is illustrated in Figure 2. It can be readily shown that under typical room conditions the values recommended in the CIBSE Guide (A5, 1979) deviate from these curves by between -15 and +300 per cent. This is principally because this section of the Guide suggests fixed values for the convection coefficients, whose values appear to be based on early data.

In common with all short-cut methods, Alamdari and Hammond's correlating equations have a number of limitations. Strictly they are only applicable for the case of rooms having smooth surfaces and an externally applied source of heat (such as underfloor heating, heated 'wallpaper', or solar-driven heat flow through solid walls : see Davis, 1983). They may also be used as a first approximation in the case of modern hot water radiators, provided they are not located beneath windows. However, a number of factors that apply to real buildings have not been accounted for in the improved correlations. Consequently it is unclear what the effect will be of, for example, surface texture or relative roughness, room element interaction (ceiling /wall and floor/wall), room fixtures and fittings, draughts, and inter-zone heat transfer. Some of these affects will be alleviated by the fact that surface-averaged heat transfer coefficients are relatively insensitive to local variations. Nevertheless, Alamdari and Hammond recommended that building thermal modellers should allow for a variation of at least ± 20 per cent in their value. Trade-offs such as this between simplicity and accuracy

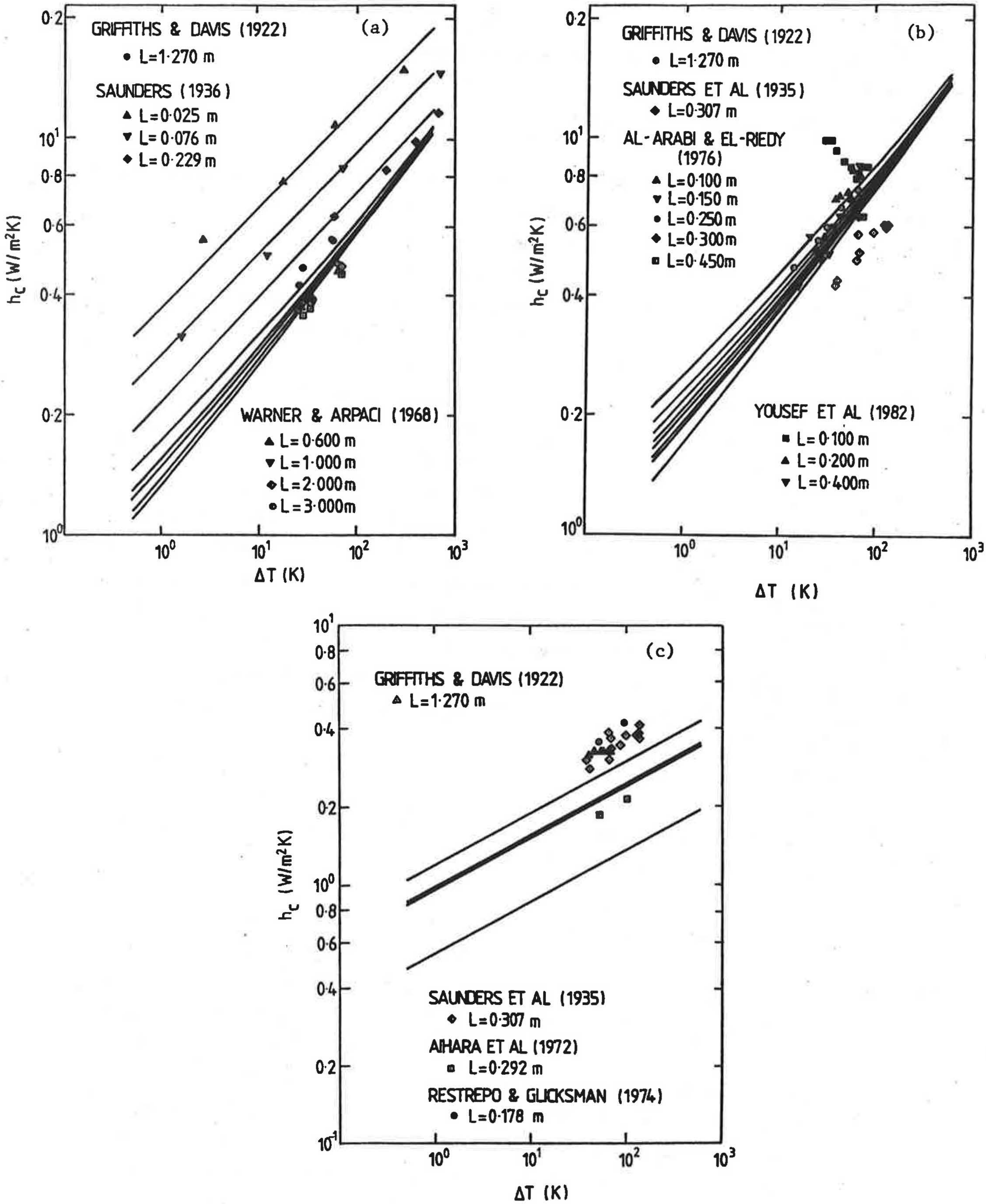


Fig. 2 Buoyancy-driven Convection from Isolated Surfaces in Air; (a) Vertical Surfaces, (b) Horizontal Surfaces (Heat Flow Upward), (c) Horizontal Surfaces (Heat Flow Downward : Stabley-stratified Layer)

are common to short-cut calculation methods.

4. Intermediate-level Methods

The Cranfield group have been involved in the development of several zonal calculation methods (see, for example, Alamdari, Hammond and Melo, 1984), including ones for convective heat transfer in warm-air heated or mechanically-ventilated rooms (the ROOM-CHT program) and air infiltration within multi-zone buildings (the FLOW program). However, in order to illustrate the potential and limitations of such methods, the model for building external convection recently reported by Gandrille, Hammond and Melo (1988) will be considered here. This has been incorporated into an intermediate-level computer code called the WIND-CHT progam. It takes account of 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. This is achieved by simulating the wind profile using a power-law expression in which the index depends on local topography. The computer is used to generalise available data correlations for the individual flow regimes that prevail around buildings, such as stagnation, boundary layer, and separated flows. Interpolation formulae, based on a cosine squared function, are then used to estimate surface convection coefficients for wind directions that are non-orthogonal to the building surfaces. Although external convection is normally wind-induced, the code also takes account of the influence of buoyancy-driven motion at low wind speeds.

An isometric view of the distribution of the convective heat transfer coefficient over a windward facade as computed by the WIND-CHT program is shown in Figure 3. It is presented as a function of wind speed and angle of attack, and illustrates, quite dramatically, the ability of the model to account for these factors. The former is seen to have a much larger effect than the latter. A comparison between the computations of the WIND-CHT program and experimental measurements obtained on the city centre multi-storey Arts Building at Sheffield University is depicted in Figure 4. These demonstrate the ability of the intermediate-level code to account for the influence of building height relative to that of the atmospheric boundary layer. Data correlations recommended in the CIBSE Guide and by the ASHRAE Task Group are also displayed in Figure 4 for comparison purposes.

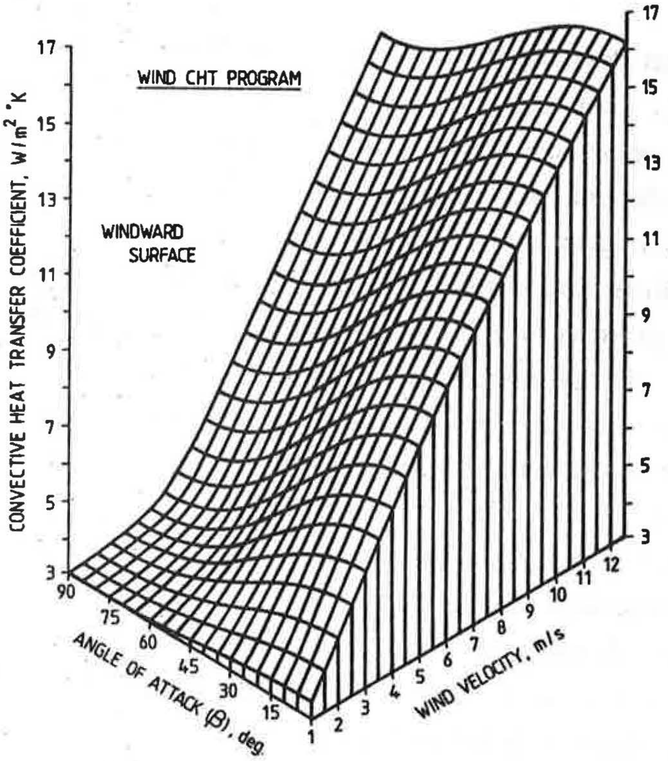


Fig. 3. Wind-induced Convection on a Vertical Windward Surface

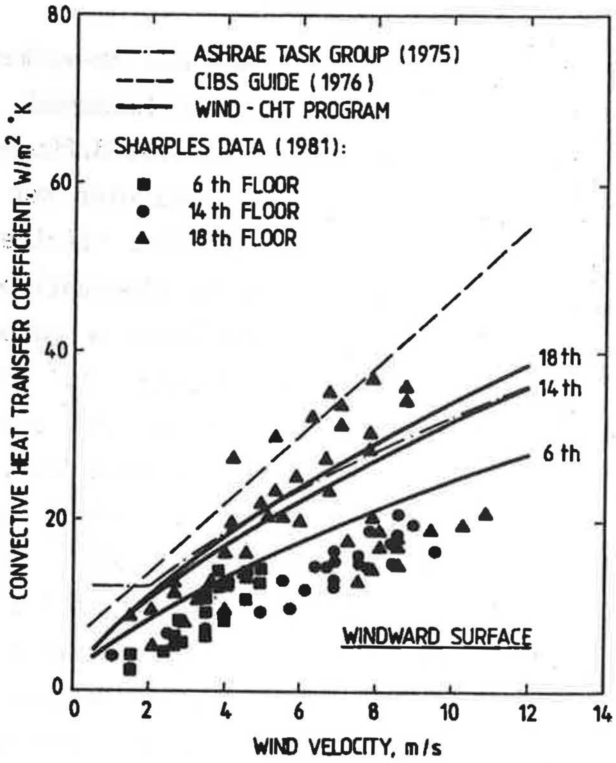


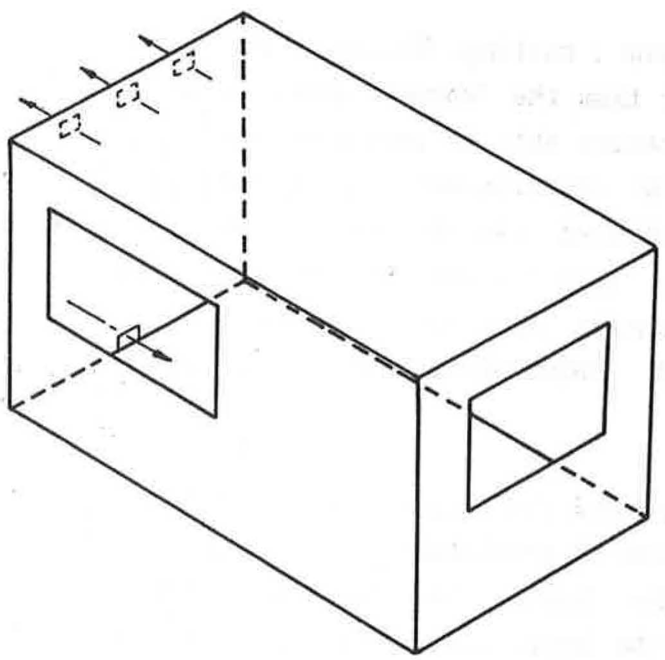
Fig. 4. Experimental Comparison with Computations : Sheffield University Arts Tower

The author and his co-workers have demonstrated that their intermediate-level models can be fairly readily incorporated into building energy simulation programs as subroutines, with only a modest increase in computing requirements. Although more general than lower-level methods, zonal models have a restricted range of application. They consequently need to be used in conjunction with a flow classification scheme. However, this is not a serious weakness as perhaps five variants would be able to handle the normal situations found in the built environment. Nevertheless, it must be emphasised that the Cranfield intermediate-level models rely for their success on both short-cut and field methods. The latter, together with experimental data, provide the basis for developing and verifying the zonal models.

5. Higher-level Methods

The author and his co-workers have developed a 'field' model (see Alamdari, Hammond and Mohammad, 1986), that solves a discretized form of the governing partial differential equations formulated in terms of pressure-velocity variables for a predetermined-size, staggered grid. It utilises the popular 'finite-domain' approach, and has the option of using a range of alternative differencing schemes. The model has been incorporated into a computer program called ESCEAT that was produced specifically to handle three-dimensional geometries. (Technical details of the code will not be given in the present contribution as they have been fully reported elsewhere, and in any case are similar to that of other finite-domain models.) The capabilities of this model, used here simply as an exemplar of its type, will be demonstrated for the purposes of computing airflow and convective heat exchange within a mechanically-ventilated, rectangular enclosure for which buoyancy effects are significant. This represented the warm-air heated room shown schematically in Figure 5, for which computations were also made using the intermediate-level, ROOM-CHT program. In a monitoring study of over thirty rooms of various shapes and sizes heated by a fan 'convector', Yaneske and Forrest (1978) found the room-averaged convection coefficient to be 6.31 W/m^2K (compared with a value of 3 W/m^2K recommended in the CIBSE Guide), but with a wide scatter. The motivation of the Cranfield studies has therefore been to develop improved methods for calculating surface coefficients in forced convective heating situations.

The velocity vector diagram shown in Figure 6 illustrates the flow pattern within the warm-air heated room under full load (winter) conditions. It can be seen that the computed flow field is strongly influenced by buoyancy effects, due to the high temperature of the supply air and counteracting cold downdraught induced by the windows. The ability of high-level flow models to simulate complex flows, such as this, are their major achievement in comparison with intermediate-level ones. The latter would be inadequate for determining, for example, the thermal comfort conditions in the occupation zone, which would require a high-level simulation. However, the far greater computer resources that field models require, compared with simpler calculation methods, would prohibit their direct use in providing input heat transfer data for building thermal simulation programs. The latter require surface-averaged convection



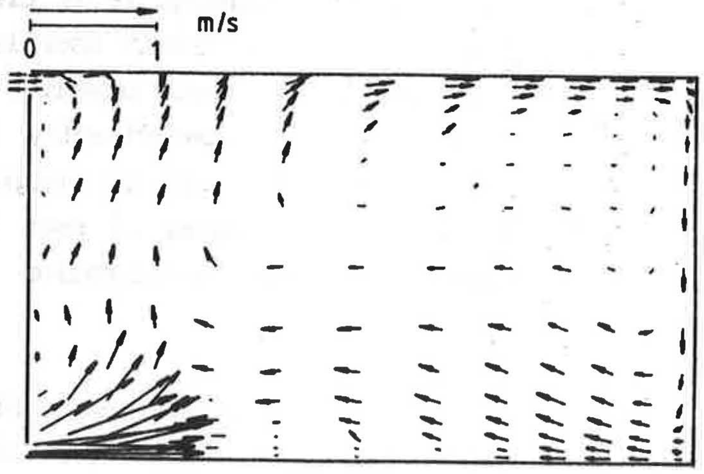


Fig. 5. Schematic Diagram of a Warm-air Heated Room with 'Low Side-wall Register'.

Fig. 6. Flow Field Velocity Vectors at the Room Mid-plane Computed via the ESCEAT Code.

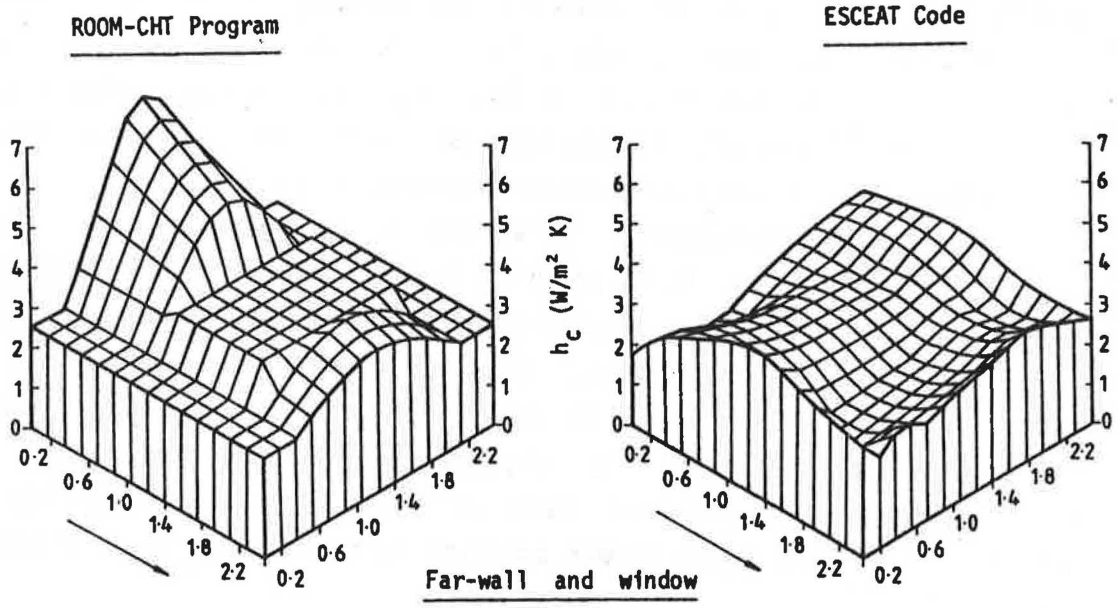


Fig. 7. Room Surface Heat Transfer : Comparison of Intermediate and Higher-level Models

coefficients for each building element : ceiling, floors, roofs, walls and windows. Although it is clear from the 'carpet' plots shown in Figure 7 that the ESCEAT code is better able to determine the local distribution of heat transfer, the corresponding surface-averaged values are not significantly different (in general) from those obtained with the ROOM-CHT program. A better use of high-level flow models in the context of heat transfer would therefore be for the development and verification of intermediate-level calculation methods.

The current generation of high-level CFD computer codes exhibit a number of limitations in terms of both physical/mathematical modelling and numerics. In regard to the former, the Reynolds numbers applicable to many flows within the built environment are in the transition range, which cannot be simulated by these codes. Even in the turbulent flow regime, there is no universal turbulence model that can reflect the full variety of complex flows observed in buildings. In these flows it is necessary to bridge the steep property gradients near surfaces using so-called 'wall functions'. These are algebraic functions that are not appropriate for recirculating flows, and will give rise to errors in, for example, heat transfer calculations. In addition, the 'standard' wall functions used in most high-level flow models apply only to smooth surfaces. Preliminary results of studies at Cranfield (see Hammond, 1987) have indicated that the sort of surface roughness encountered on buildings may increase the wall heat-flux by up to nearly 300 per cent of smooth surface values. This is in general agreement with data for external convection given in the ASHRAE Handbook of Fundamentals. In terms of the numerical aspects of calculation procedures, it is usual to employ relatively coarse grids which may result in errors near critical components, such as supply apertures and recessed windows. Flow boundary conditions are also often specified on the basis of analytical or experimental results, and are problem-specific. The computational requirements for field CFD programs are of the same order as 'finite difference' building thermal models, and hence direct coupling is impractical as suggested earlier.

There are several 'schools of thought' as to the most appropriate measurable quantities for validating thermo-fluid calculation methods. Gosman, Neilsen, Restivo and Whitelaw (1980) measured time-averaged velocity and temperature distributions within a model-scale, mechanically-ventilated enclosure in order to validate their CFD code.

In contrast, Durst, Melling and Whitelaw (1976) advocate the use of turbulence data, either turbulent stress and heat-flux measurements or the measurement of the higher-order terms in the 'transport equations' associated with turbulence models. More recently, Chieng and Launder (1980) have recommended using local heat transfer distributions on boundary surfaces, as these are sensitive to both outer flow and near-wall modelling. Experience at Cranfield suggests that most intermediate and higher-level calculation methods can be made to ensure reasonable agreement with the mean flow, while turbulence properties tend to be difficult to measure and/or are model-dependent. Heat and mass transfer coefficients are more readily measured, and are therefore ideal candidates for refining and verifying calculation methods. They are consequently the preferred source of validation data used by the author and his co-workers (see, for example, Alamdari, Hammond and Montazerin, 1986).

6. Possible Task Group 'Action Areas'

In many respects building airflow modelling is in its infancy, and therefore the challenge facing the BEPAC 'Air Movement' Task Group is to bring a coherent view to this important and rapidly developing field. There is considerable support within the community for the Group to carry out its deliberations against the background of a model classication scheme like the one outlined above. It is clear that thermo-fluid models at all three 'levels' have both strengths and weaknesses. They will inevitably continue to be developed and used in the context of building environmental performance analysis. 'Action areas' for the Task Group might therefore include:

- Practitioner requirements : Identify the needs of the users of the different types of models for airflow and related phenomena. These should be specified in terms of accuracy, economy and user-friendliness.

- Register : Catalogue existing algorithms/models, and their perceived strengths and defects. Attempts to indicate the quality of computer implementation in each case.

- Reviews : Encourage the production of state-of-the-art reviews in critical areas. This might best be done in collaboration with the wider computational thermo-fluid dynamics community.

- Case studies : There is a need to identify a relatively small number of building/HVAC system combinations that could be used as test cases by both experimentalists and (building and thermo-fluids) modellers.

- Validation : Encourage the development of standard data sets (benchmark tests) and procedures for verifying the different types of models.

- Future research needs : The above will inevitably lead to the identification of areas needing further research. The Task Group could attempt to highlight these, and bring them to the attention of the research community and their funding bodies.

7. Acknowledgements

The research on the computation of building airflow, convective heat exchange, and contaminant dispersion at Cranfield has been very much a team effort. The specific work referred to in the paper was mainly undertaken during 1980-86. The author would therefore wish to acknowledge the important contributions of his research associates during this period, particularly Drs Farshad Alamdari, Claudio Melo, Wahid S. Mohammad, Nader Montazerin, and Dubravka Vasilic-Melling.

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