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An Overview of Combined Modelling of Heat Transport and Air Movement

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John Kendrick

Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-one IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D). This is achieved in part through a programme of collaborative RD&D consisting of forty-two Implementing Agreements, containing a total of over eighty separate energy RD&D projects. This publication forms one element of this programme.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy. Seventeen countries have elected to participate in this area and have designated contracting parties to the Implementing Agreement covering collaborative research in this area. The designation by governments of a number of private organisations, as well as universities and government laboratories, as contracting parties, has provided a broader range of expertise to tackle the projects in the different technology areas than would have been the case if participation was restricted to governments. The importance of associating industry with government sponsored energy research and development is recognized in the IEA, and every effort is made to encourage this trend.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures that all projects fit into a pre-determined strategy, without unnecessary overlap or duplication but with effective liaison and communication. The Executive Committee has initiated the following projects to date (completed projects are identified by *):

I Load Energy Determination of Buildings*
II Ekistics and Advanced Community Energy Systems*
III Energy Conservation in Residential Buildings*
IV Glasgow Commercial Building Monitoring*

V Air Infiltration and Ventilation Centre
VI Energy Systems and Design of Communities*
VII Local Government Energy Planning*
VIII Inhabitant Behaviour with Regard to Ventilation*
IX Minimum Ventilation Rates*
X Building HVAC Systems Simulation*
XI Energy Auditing*
XII Windows and Fenestration*
XIII Energy Management in Hospitals*
XIV Condensation*
XV Energy Efficiency in Schools*
XVI BEMS - 1: Energy Management Procedures*
XVII BEMS - 2: Evaluation and Emulation Techniques
XVIII Demand Controlled Ventilating Systems*
XIX Low Slope Roof Systems
XX Air Flow Patterns within Buildings*
XXI Thermal Modelling
XXII Energy Efficient Communities
XXIII Multizone Air Flow Modelling (COMIS)
XXIV Heat Air and Moisture Transfer in Envelopes
XXV Real Time HEVAC Simulation
XXVI Energy Efficient Ventilation of Large Enclosures
XXVII Evaluation and Demonstration of Domestic Ventilation Systems

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous aggreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Germany, Finland, France, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

Contents

An Overview of Combined Modelling of Heat Transport and Air Movement

Introduction

Increasing design standards within the building industry mean that some form of pre-construction testing of the building envelope is required. Expensive and time consuming field tests are becoming more impractical whereas the cost-effectiveness and greater flexibility of computer simulations allow them to play an increasing role in building design. The designer is responsible for the climate that exists within the building so accurate modelling of the proposed building is a prime concern in the creation of a new building plan. In the past, thermal simulation has tended to be separated from that of detailed air movement modelling but, more recently, efforts have been made to combine these aspects. This is particularly important since air flow can have a significant influence on the energy budget of a building as well as having important air quality and comfort consequences.

Detailed modelling has advantages over the commonly used experimental techniques. The actual equations that describe a fluid flow process are solved. This leads to a better understanding of the problem and ultimately more confidence in a design. Empirical approaches to design, such as rules of thumb and correlations, say nothing of the physics of the problem and are usually of limited applicability. Modelling can provide a complete picture of the flow whereas experimental techniques can usually only provide a limited view from pre-selected measurement positions.

Building energy use is also of increasing concern to the building designer and occupier, especially as concern arises over the influence of energy use on global pollution. It has been estimated that building services account for about one fifth of the primary energy consumption in industrialised countries (Boxer 1991). The need for the efficient use of energy is therefore of primary concern. In order to develop realistic methods for the design of buildings, it is necessary to simulate the dynamic response of the building, coupled with the transport of that energy within the structure. This requires quite complex computational techniques and has directed the research in the direction of modelling the performance of the building fabric. The air flow and convective heat exchange in and around the building structure have to date been simulated using only rough approximations. The accuracy of these simulations is greatly dependent on the input data supplied to the prediction.

The factors used in the determination of temperature and air movement within buildings are often connected in a complex manner. Solar radiation, external air temperature, wind strength and direction, size of openings, and building fabric thermal properties all play a part in determining the air temperature and heat distribution at any time of day. Any mathematical model used to simulate building conditions must tackle all these complex interactions.

A fundamental objective of this report is to investigate the techniques used in the design and research fields for the evaluation of thermal and air flow simulations. The scope is restricted to the whole building rather than flow and heat transfer within individual structural elements (eg. cavity walls).

Considerable developments are taking place in the field of air flow and thermal simulation. Rather than present an in-depth study of these developments, this report concentrates on the rather more general aspects of the combined simulation. Bibliographical references are restricted to publications taken from the Air Infiltration and Ventilation Centre's Bibliographic Database - AIRBASE, which illustrates specific building examples and case studies.

2 Application Areas

Thermal and airflow models can be applied in a number of different ways during the process of designing and operating a building. In assessing the suitability of different modelling techniques, it is important that the various approaches to analysing thermal performance are set into the proper context of applications needs. The following sections identify a number of applications areas where thermal models are used, and seeks to identify key factors which influence the selection of model complexity.

2.1 Design of Heating and Cooling Systems

Traditionally, the main application for thermal models has been to help size HVAC system components. This will include

- room units (radiators, air flow terminals)

- central plant (boilers, chillers)

The techniques used for such exercises vary from simple steady state methods, right through to full dynamic simulation. The choice of technique is a trade off between speed and rigor.

Sizing of equipment is concerned with providing adequate plant capacity to meet a particular design condition (cold day, hot day etc). The design condition is associated with a degree of acceptable risk, i.e. the designer does not aim to meet every conceivable condition, but rather to ensure the system can cope with an acceptable proportion of the anticipated climatic conditions. To that end, the simpler methods make gross assumptions about weather patterns and the operation of the building in arriving at an acceptable plant size. Margins to cater for other factors (e.g. intermittent operation) are then added to arrive at the required plant capacity. This approach can result in oversizing of plant, which is wasteful in capital costs, and can also result in reduced operating efficiency. At the other extreme, full simulation can explore how the building and system respond to real patterns of weather and use, and determine the plant capacities to maintain acceptable comfort conditions. However, such detailed methods require much more information (e.g. schedules of occupancy, levels of internal gains etc). These may not be known precisely at the design stage, particularly if the development is a speculative one with no clearly defined occupier. It must therefore be appreciated that although the calculation method is perhaps more credible, it is being used with data which is itself uncertain, and therefore the end result may be no more reliable than a much simpler method, particularly if applied by an experienced design engineer.

The main benefit that more detailed simulation tools can offer is in design optimisation. There is an increasing awareness of the need to consider building fabric and HVAC systems as an integrated design exercise, rather than as independent processes. Such an integrated approach relies on the dynamics of heat transmission and storage in the building fabric, and demands a fairly detailed level of analysis. For example, the designer might want to explore the potential for precooling the building structure by night time ventilation as a means of reducing the installed capacity of chiller plant.

2.2 Design of ventilation systems

Ventilation system design is concerned with delivering the right quantities of fresh air to the right place in an energy efficient way. Air movement is driven by both natural and mechanical forces, and the magnitude of these forces is often influenced by the overall thermal environment. This is most notable in the context of natural ventilation strategies, but also in other systems which rely on natural convection to move the air (e.g. displacement ventilation).

As in section 2.1, there are simple design procedures which can be followed to achieve a solution which will work in most cases, at least in terms of delivering minimum fresh air quantities (eg. providing certain ventilation openings related to floor area etc.). However the problem is much greater if the ventilation system is also used as the primary mechanism for controlling summer overheating. In this context, the ventilation system design is less about fresh air and more about cooling capacity. This demands that the design can deliver the required air change rates, and this involves an interaction between envelope leakage distribution, wind pressures and temperature variations. Typical thermal models will assume the air change rates, and predict the resultant temperature distribution. Multi-zone ventilation models will assume a temperature distribution and predict the air change rates. The problem is that of course these parameters are not independent, a problem which is further exacerbated by the thermal inertia of the building fabric. Combined modelling of air flow and heat transport can address these interactions directly.

Another aspect relating to ventilation system design is in the analysis of contaminant transport. Indoor air quality is of increasing importance to building owners and occupiers, and air quality requires an understanding of pollutant sources, sinks and transport mechanisms. The previous paragraphs have already indicated the benefits of detailed modelling in predicting the likely pattern of air movement. Air movement is the main transport mechanism for moving pollutants around the building, but the thermal environment has another important influence on air quality, in that evidence has shown that pollutant source strengths (e.g.outgassing from building materials) can be temperature and/or humidity dependent.

2.3 Analysis of Energy Performance

Another application area for thermal models is in the estimation of building energy performance. This was of great interest in the late seventies and early eighties as a consequence of the oil crises and concerns over non renewable energy resources. It is becoming increasingly important again in the early nineties because of concern over CO2 emissions and climate change.

By definition, analysis of energy use is primarily concerned with long time sequences, usually a full year, or at least a heating or cooling season. Again there are a range of methods which can be applied to predict energy consumption. These range from steady state models using period average data, right through to simulations of building, plant and controls at time steps of minutes. Most of the arguments which have been presented in sections 2.1 and 2.2 apply to the estimations of annual energy performance. However over and above those considerations is the fact that periods of maximum energy wastage frequently occur in mid-season conditions, when heating and or cooling demands are low. At such times, plant may be cycling rapidly (and thus operating inefficiently), or there may be significant mixing losses if heating and cooling plant are fighting against each other. The way the plant will be responding to a control strategy which modulates plant response as a function of measured space conditions. Detailed modelling can predict these conditions, and hence the plant response and energy usage.

Such detailed modelling is particularly important in the context of passive solar design, where the aim is to maximise the benefit of 'free' energy. Solar gain only offers an energy benefit when there is a heating demand in the zone, thereafter it becomes an energy or comfort penalty. In commercial buildings with high internal gains, even in winter there is often a significant cooling demand after the morning warm up period. Therefore the analysis of passive solar benefits requires a clear analysis of the dynamics of the demand and availability of passive solar energy. The utilization of passive solar gain in a building often relies on air movement to transport the captured solar heat to the point of heat demand.

3 Needs for Detailed Understanding of Convective Flows in Buildings

Air movement effects building thermal performance in a number of inter-related ways. As a result of increasing thermal insulation standards, ventilation is becoming the dominant factor in the energy balance of a building. Air movement around and within buildings also effects thermal performance by influencing the rate of heat transfer from the building fabric to the air. Air movement is also a primary mechanism for conditioning the thermal environment of a space, either directly by the mechanical injection of conditioned air into the space, or indirectly by natural convection flows generated by the heated (or cooled) surfaces such as radiators or chilled ceilings (Stahl and Keller 1992). Air movement is also the primary mechanism for pollutant transport within buildings. From the above, it can be seen that air movement has a profound effect on energy, comfort and air quality. It is therefore essential that building designers have a full understanding of how air movement interacts with the overall building thermal and pollutant transport processes; the following paragraphs give more detail on each of these interactions, and highlights the need for better combined heat transport and air flow modelling.

3.1 Ventilation Energy Losses

In well insulated buildings, the ventilation energy loss can often represent up to 50% of the total heating energy demand. It is therefore self evident that the estimation of the ventilation energy loss be as precise as possible. Fig 1 below shows how infiltration rates vary with the changes in climate and occupant behaviour in a typical building. The relationship between natural ventilation rate and inside-outside temperature difference is non-linear, and so the seasonal energy loss is not directly proportional to the product of average flow rate and average temperature difference. Because the flow rate is itself a function of the temperature difference, and the internal temperature is influenced by the rate of room energy loss, there is a strong interaction between the two parameters, especially at low wind speeds.

There is increasing interest in using natural ventilation as a means of controlling summer overheating. The same arguments as are outlined above also apply to the summer cooling situation. This highlights the fact that making simplified assumptions of fixed air exchange rates when modelling building performance can lead to some very misleading conclusions.

3.2 Convective Heat Transfer

Surface convection is a process by which the heat flux, emanating from some transparent or opaque surface, is transmitted to the adjacent fluid layer. For building surfaces it is usual to differentiate between internal and external exposures. In the latter case convection is usually considered as forced whereas, with internal surfaces, natural and/or forced air movement can be assumed, depending on the type of mechanical ventilation and the convective field it generates.

Forced convection is a function of the prevailing fluid flow vector. Typically, for external building surfaces, wind speed and direction data are available for some reference height and simple techniques exist to estimate vertical velocity profiles. Forced convection for internal surfaces is more of a problem, requiring the knowledge of the distribution and operation of air handling equipment and heat emitters, and the nature of the boundary layer at each surface position.

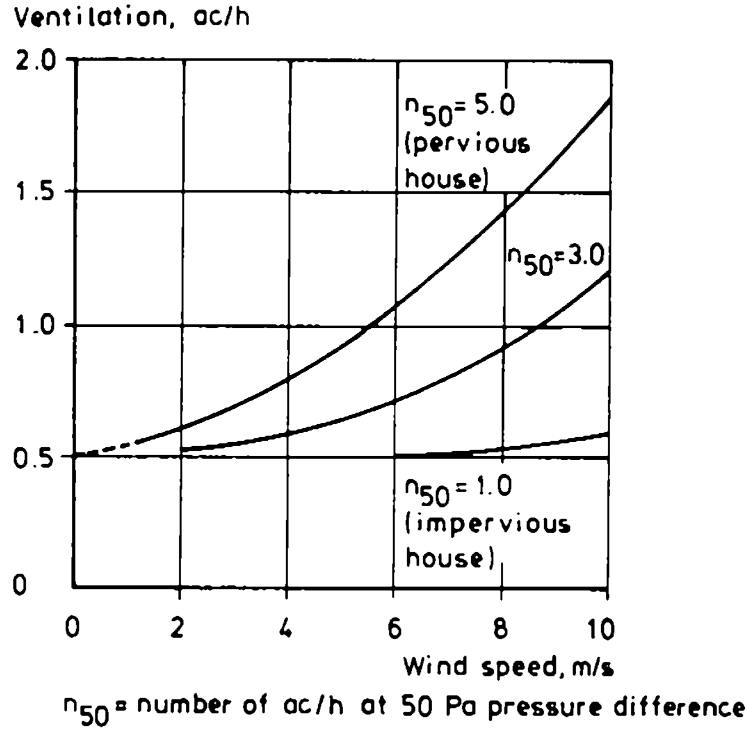

Figure 1: Ventilation Rate against Wind Speed

Natural convection is an easier problem to study and many formulations have emerged which expresses coefficients as simple functions of the surface-to-fluid temperature difference; surface aspect, roughness and dimension; direction of heat flow.

It is normal practice in simulation modelling to make use of dimensioned convection coefficients (W m-2 C-1) which represent some average value for a particular finite surface area but can change with time. Accurate values of surface heat transfer coefficients are not often known, however appropriate values can be found in the CIBSE guide (CIBSE, UK 1986), ASHRAE, and VDI (Germany). Recently, Alamdari and Hammond (1982) have produced correlation expressions to allow the estimation of time-dependent but surface-averaged convection coefficients.

As insulation standards improve, the importance of this effect will be reduced, since the dominant resistances to heat flow will be more in the structure of the building and less in the film resistances at each surface. The relative importance of the effect can be seen from the typical wall and window constructions below, where the various component resistances are given, along with the likely variation in surface convection coefficients.

Layer	**Thickness** (m)	**Conductivity** (W/K m)	**Resistance** (sq.m K/W)
Concrete Block	.200	.190	1.053
Air Gap	.025		0.180
Polystyrene	.025	.030	0.833
Gypsum Plaster Board	.010	.160	0.063
			2.128

For a wall with sheltered exposure:

Outside surface resistance = 0.102 sq.m K/W
Inside Surface resistance = 0.117 sq.m K/W
Thermal transmittance U-value = 0.426 W/sq.m K

For a wall with severe exposure:

Outside surface resistance = 0.009 sq.m K/W
Inside surface resistance = 0.117 sq.m K/W
Thermal transmittance U-value = 0.443 W/sq.m K

For a sheltered exposure double glazed window:

Outside surface resistance = 0.102 sq.m K/W
Inside surface resistance = 0.117 sq.m K/W
Thermal transmittance U-value = 2.51 W/sq.m K

For a double glazed window with severe exposure:

Outside surface resistance = 0.009 sq.m K/W
Inside surface resistance = 0.117 sq.m K/W
Thermal transmittance U-value = 3.260 W/sq.m K

Figure 2: Typical Wall Construction and U-values

The U-value of the wall is increased by about 4%, whereas that of the double glazed window by nearly 30% due to the changes in surface heat transfer coefficient for the likely range of wind exposures.

3.3 HVAC System Performance.

HVAC systems are designed and controlled to deliver (or extract) heat to maintain the required thermal comfort conditions. With forced air systems, the momentum of the supply dominates the air movement processes, and so there is little feedback from the room to the supply system other than through the modulating influence of the control strategy. However there is an increasing interest in systems which rely on natural rather than forced convection (displacement ventilation, chilled ceilings, chilled beams etc.) With such systems, the mechanisms which drive the air are the heat transfer processes going on within the space, and so there is a clear need to understand and to be able to predict these interactions.

This does not mean that it is always necessary to model in detail the convective flows, but rather to appreciate the influence that different thermal effects may have on the performance of such systems. An analogy can be made with the modelling of hot water radiators, which also rely on natural convection. For example, their proper application requires an appreciation of the way the buoyant air from the radiator interacts with cold down draught from the window, and the importance of back losses when installed on outside walls. Performance criteria have been developed through measurements and detailed modelling work, and these simpler procedures incorporated in thermal simulation models.

3.4 Stratification

In most thermal models there is an implicit assumption that the air in any one zone is fully mixed, i.e. there are no variations in air temperature within the zone. Such assumptions are reasonable in many situations, but there is an increasing tendency to design to achieve stratification in the space. Reference has already been made to displacement ventilation, but another example is that of atria design where the intent is to capture the heat at the top of the atria to promote stack ventilation in the summer and avoid excessive temperatures in the occupied zone. Some atria are also used to capture and pre-heat ventilation air in winter.

By definition, atria are coupled to the rest of the building, and so the distribution of temperature with height up the atrium will influence the conduction and ventilation energy exchanges with different floors of the main building. In most atria, the pattern of air movement is strongly influenced by, if not entirely due, to natural convection. The solar radiation will fall on various opaque surfaces of the atrium, (walls, floors etc), heating them up and generating buoyant plumes. In winter and mid season, areas of the atrium glazing may be cold, resulting in down draughts and recirculation. It is clear that a full understanding of all the energy flow paths is needed to achieve an effective design. This is one of the most challenging areas for thermal modelling, and has resulted in the initiation of a new IEA project in this area.

3.5 Pollutant Transport

In the past, the design emphasis has been on thermal comfort, but with the advent of new materials and a concern to achieve energy efficient ventilation, increasing attention is being given to air quality control. Air movement is the main means for pollutant transport within buildings. The previous sections have indicated how air movement is affected by the thermal environment. However the thermal environment also has a significant effect on other aspects of IAQ control. Pollutant transport is concerned not just with air movement, but also with pollutant sources and sinks. The strengths of such source and sink terms can be temperature and humidity dependent.

The accurate prediction of pollutant transport must therefore include all of these factors in sufficient detail. Gross approximations in one of the parameters could greatly affect the prediction. Temperature differences can alter the stratification within an enclosure and then will influence the distribution of the pollutant source.

4 Potential Users of Models

There are three main classes of potential users of models, each of whom will have different requirements. These model users are

Building designers and operators

Government policy makers

Research scientists

Although the principal requirements of each group is different, they inter-relate and so it is important to see how each users needs and products can help the others.

The primary objective of developing thermal models must be to enhance the design process such that the energy and environmental performance of buildings is improved. Therefore the architect and engineer must be seen as the key user to which model development must be targeted. Designers will be using models to address all the applications defined in section 3. It must be recognised that different stages of

the design process require different levels of modelling complexity and sophistication. At the early stages of design, different options need to be explored very quickly to identify the important design parameters, and to home in on a design concept. As the design firms up, so more refined tools are required to optimise the design, particularly in the context of the increasing interest in passive and hybrid buildings.

In order to use models, designers have to be convinced of the benefits of modelling, and to be confident of the ability of the program to model the complexities of real buildings. To achieve this enhanced appreciation of the benefits of modelling, more emphasis should be placed on reporting well documented case studies which illustrate how models have been used to solve real design problems. The next stage is to present the user with an interface to the model which is easily understood and used. Experience has shown that one of the biggest failures in the application of models is the inappropriate choice of modelling strategies and/or input data. This highlights the fact that as much effort has to go into educating the user to make proper use of existing models as must go into developing new models. IEA Annex 21 is very much focused on just these issues.

In developing the design for a building, one of the main constraining influences on the design is the regulatory codes and standards which control such factors as thermal performance, fresh air rates etc. Such codes are set at a national level, and are the province of the government policy maker. Such policies are based on credible scientific data, often involving the use of models to establish the basis of appropriate energy targets etc. For the policy maker, models need to be capable of operating at a higher level than an individual building, since the government is also concerned with the implications for the whole national building stock. This means that simpler aggregated models are very useful in assessing energy performance at a national level. These are often based on regression equations based on measured data, and using established modelling methods to test, for example, the effect of revised U-values on national energy use.

The researcher is primarily concerned with improving models for use by the other two groups. This means he must be fully aware of the real needs of the other groups, and the limitations in their knowledge of the subject. A surprisingly small proportion of a designers time is actually spent on doing design, the balance being contract management, information production etc. The designer cannot therefore be expected to be a technical expert on all aspects of building performance, and so the researcher should be helping to equip the designer with tools that will enable him to apply specialist expertise through the use of a model.

Because of the increasing emphasis on passive buildings, designers are realising that they need to better understand the dynamic thermal processes going on in a building. This is driving the need for improved and enhanced models which are able to explicitly address all the interactions that take place in a real building. The researcher plays the key role in this model development process. Firstly he will use a total building thermal model to drive a newly developed algorithm which has been developed to better model a particular thermophysical process. This places a high degree of importance on the architecture of the program, since it should allow different algorithms to be incorporated easily into the overall model framework.

This is a second area for the researcher, and much effort is now being put into developing such object oriented models (the Kernel system in the U.K. and the SPANK system in the USA (Sowell, BEPAC Conference 1991, Buhl et al, 1991)). The second important use of detailed models is to use them as the basis of simpler assessment methods. This can be done by running a range of parametric analyses to develop performance charts and design guidance which can be very helpful in the early stages of the design process.

A third area in which researchers must have a key role is in the development of reliable databases to support the use of models. As programs become more sophisticated, they require more and more input data, much of which is not readily available. Chapman (BEPAC 1991) presents an interesting analysis which documents the use of a series of models being used by trained users. He suggests that the potential benefit of more complex modelling can be more than offset by the increased probability of making input errors. This problem must be addressed by better and more comprehensive databases, supplemented by systems to support the model user in selecting the correct data item for his application.

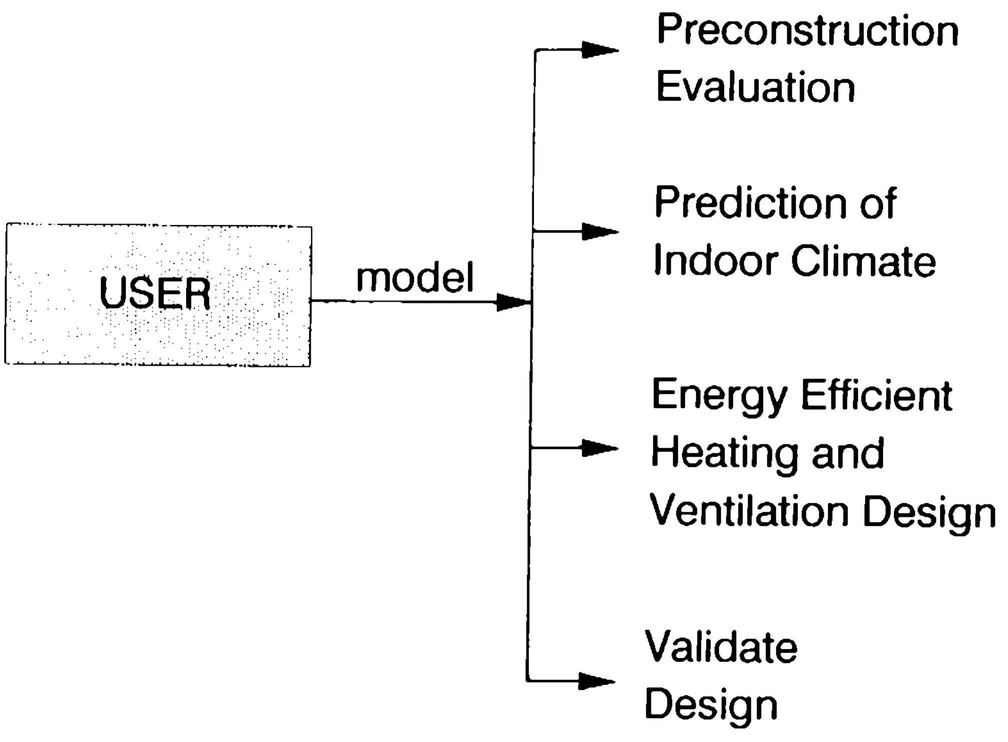

Figure 3: The Needs of the User

5 Levels of Detail and Transport Mechanisms

Heat is transferred by conduction, convection and radiation. Within a building the physical processes to be modelled are:

Conduction - passage of heat through the building elements.
Convection - interchange of heat between the building element and the air exchange in and between rooms.
Radiation - interchange of heat between building surfaces, or the transfer of heat from high temperature sources.

5.1 Transient Conduction

This is the process by which a fluctuation of heat flux at one boundary of a solid material finds its way to another boundary, being diminished in magnitude due to the thermal storage, and shifted in time. Within the building fabric, transient conduction is a function of the temperature and energy excitations at the surfaces, the temperature/time dependent thermo-physical properties of the individual materials, and their relative positions. For modelling and simulation purposes it is usual to describe external climatic information as time-series data with the objective to determine internal transient energy flow and hence the dynamic variation of heat flux at internal surfaces.

The thermo-physical properties of interest include conductivity, density and specific heat capacity as well as physical dimensions. These properties are time-dependent because of intra-material temperature and/or moisture fluctuations. However in many applications, such dependencies are ignored and properties are assumed to be time invariant. Materials with high thermal diffusivity values (conductivity divided by the product of density and specific heat) transmit boundary heat flux fluctuations more rapidly than materials with low values. Annex 14 (1990) list the basic thermo-physical properties of a range of materials.

5.2 Radiative Exchanges

5.2.1 Long wave radiation

Heat transfer by longwave radiation exchange between two or more surfaces in visual line of each other is an important part of building energy simulation but is one which introduces mathematical complexities due to non-linear behaviour and the complexities caused by building geometries and obstructions.

5.2.2 Shortwave radiation

In most buildings the gain of energy from shortwave radiation into the construction, will constitute a significant proportion of the building loading. Therefore an accurate prediction of the shortwave flow paths can greatly influence the reliability of the model to predict loading and temperatures.

Some portion of the shortwave energy arriving at a surface will find its way into the structure and will contribute to the internal heat flux. With transparent structures, the shortwave energy impinging on the outer surface is partially reflected and partially transmitted. Within the layers of the fabric there will be further reflections and transfers and some of the energy will be absorbed, resulting in a temperature rise of the fabric. This temperature rise will add to the transient conduction. This will raise the inside/outside temperature difference which, in turn, drives the surface convection and radiation flow paths.

5.3 Convection

In building simulations it is usual to consider convection coefficients separately for internal and external surfaces. It is also often necessary to consider the differences between natural and forced convection.

5.3.1 Natural Convection

When a fluid comes into contact with a heated surface, conductive heat transfer takes place and there are temperature variations established within the fluid, these variations then create density variations within the fluid. Buoyancy forces then create motion with the fluid to carry away the conducted heat from the surface. This is known as natural (or buoyancy driven) convection. Resulting fluid flows will either be laminar, in which each fluid particle will follow a distinct streamline and does not come into contact with other streams, or turbulent, in which the fluid particles can cross streamlines to increase the capability for heat transfer.

5.3.2 Forced Convection

When the fluid motion is influenced by some external force, such as the wind or a fan then the convection is described as being forced. In this case then there needs to be the consideration of other dimensionless groups, for any calculations, such as Reynolds number (Re).

5.4 Combined Convection and Radiation

Several simulation techniques do not separately model convection and radiation, but rather use a combined heat transfer coefficient for a space. One internal temperature is calculated for the space which is a mean weighted average typically 2/3 of the mean radiant and 1/3 of the air temperature. This means that the conduction heat loss is correctly calculated, but the ventilation heat loss will be in error in proportion to the difference between the air and mean radiant temperature existing in the space.

5.5 Bulk Convection

There is also the consideration of the convection due to the bulk air movement into and within a space. This can account for a significant level of heat movement so it is a requirement of an accurate prediction to model the bulk air flows in the design space. The different ways that these air flows can be modelled are discussed in more detail in the following section.

6 Interaction of Air Flow with other Thermal Mechanisms

The following sections detail different approaches to modelling bulk air flow within a thermal model. More detailed information can be found in the AIVC Calculation Techniques Guide (Liddament 1986) and the AIVC Technical Note 33 (Liddament 1991).

6.1 Fixed air change rates

These are the methods to be found in the CIBSE Guide and ASHRAE fundamentals. This approach estimates an air change rate. There are two methods outlined in the CIBSE Guide. In the first, infiltration is calculated by graphical means using local wind speed, building height and building quality data. A basic infiltration rate is calculated based on design wind speed. Adjustments are then made to individual room rates according to the window distribution and room level. The second approach makes use of a table of expected values for buildings of typical construction.

6.2 Scheduled rate

The infiltration rate is assumed to be variable with time, and the values are approximated with the inclusion of the influence of: Base rate infiltration, day time window opening, variation of ventilation and ventilation control. Time dependent infiltration effects the heating and ventilation system and is a function of the temperature and the wind speed.

6.3 Regression Techniques

This method is based on the results of statistical fits to long term time series data of infiltration rate measurements and associated climatic data. In its basic form air infiltration is expressed as a linear function of wind and temperature (Liddament 1986).

The main value of this approach is in the extrapolation of the results beyond a measured period. Typically, hourly rates of air infiltration are continuously measured over a period of a few days. Appropriate regression coefficients are then evaluated and the performance of the air infiltration equation is verified over a further short measurement period. The regression equation may then be used to estimate air infiltration performance of the building over a wider set of climatic conditions.

The main disadvantage of this method is that the calculated regression coefficients are unique to the building since they reflect not only the air tightness performance of the building but also its orientation with respect to adjacent obstacles. It is therefore not possible to transfer the coefficients to other buildings. Although representative values of regression coefficients have been published for design purposes, they can be very unreliable.

6.4 Single zone

This method is used to calculate the infiltration into a single space. Model parameters include: Flow path (leakage) distribution, flow path characteristics, building height, internal to external temperature difference, local wind speed, local shielding conditions, terrain roughness parameters and the characteristics of any mechanical ventilation system.

A single zone network approach offers many advantages which include: Comparative ease of calculation, the addition of any number of flow paths, the inclusion of any combination of wind, stack and mechanically induced pressures, the ability to identify the flow direction and the magnitude of the flow rate through each of the defined openings, calculation of internal pressure and the ability to determine the neutral pressure plane using the external and internal pressure data (Liddament 1986).

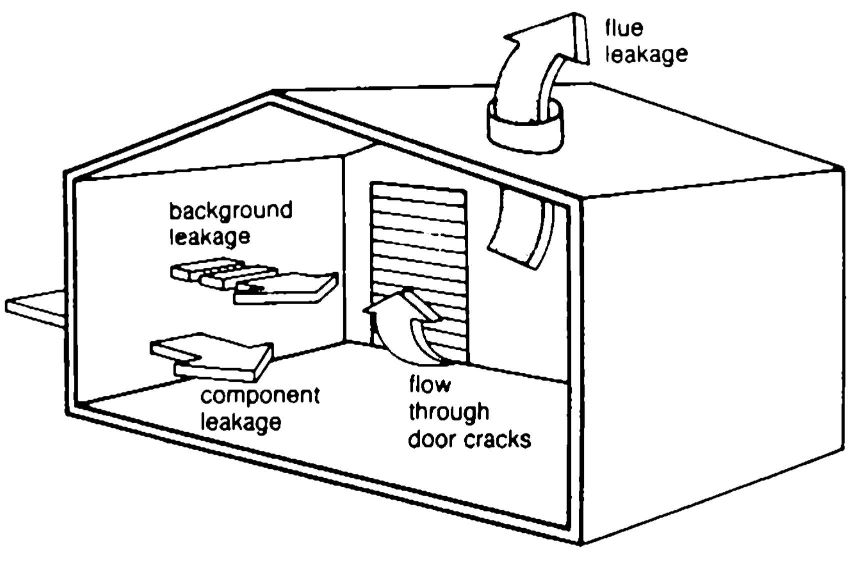

Figure 4: A Typical Single Zone Network

The principal disadvantage of a single zone approach is its unsuitability for multi zone buildings. Although it is possible to subdivide the area into an array of single zones assuming that they are isolated internally, this approach does not consider the interaction between zones. Such interactions are very important for natural ventilation strategies, pollutant transport modelling, etc.

6.5 Multi zone

If internal partitioning presents an impedance to the movement of air, then for most purposes a multi zone or multi cell approach is needed. A number of such programs have been developed for the purpose of incorporation into combined thermal and air transport models. Feustel and Dieris (1991) describe a review of the multi zone models currently in use.

Multi zone models are complex programs in their own right, and a major focus of current research activity is how such models can be coupled into detailed thermal models. It is one of the topics to be addressed by IEA Annex 23, and three methods have been proposed as described below.

6.5.1 Sequential Coupling

This is the simplest coupling method, and involves running the two programs independently. Firstly, the multi zone air flow model is run, with assumed values of zone temperatures. The air flow model is solved for each of the weather conditions (temperature, wind speed and direction) for the period of interest of the thermal simulation. This generates a schedule of zone air change rates as a function of time. These are then used in the thermal simulation as described in 6.2, the only difference being the schedule of flows has been calculated rather than assumed. The model user should confirm that the values of zone temperature assumed for the multi zone air flow model were reasonable by checking against the zone temperatures predicted by the thermal simulation. If there are significant differences, then the loop should be repeated.

6.5.2 'Ping-Pong'

The 'ping-pong method involves running the multi zone model and the thermal simulation concurrently, but independently. The thermal program will just predict the zone temperatures based on the current air exchange rates, climate etc. These temperatures are then passed onto the air flow model which will calculate a revised set of air exchanges. These will be passed back to the thermal simulation to be used for the next simulation time step. Ideally a supervisor should generate a time loop that alternately starts a one-step simulation run with the two codes involved. Each model solves its own problem with its own method. At each time step the supervisor must decide whether the solution converges, by comparing the values from one time step with the values from the previous time step and decide if the solution is valid. The advantage of this method is that if a generic coupling environment exists, various codes can be coupled without having to rewrite specific subroutines.

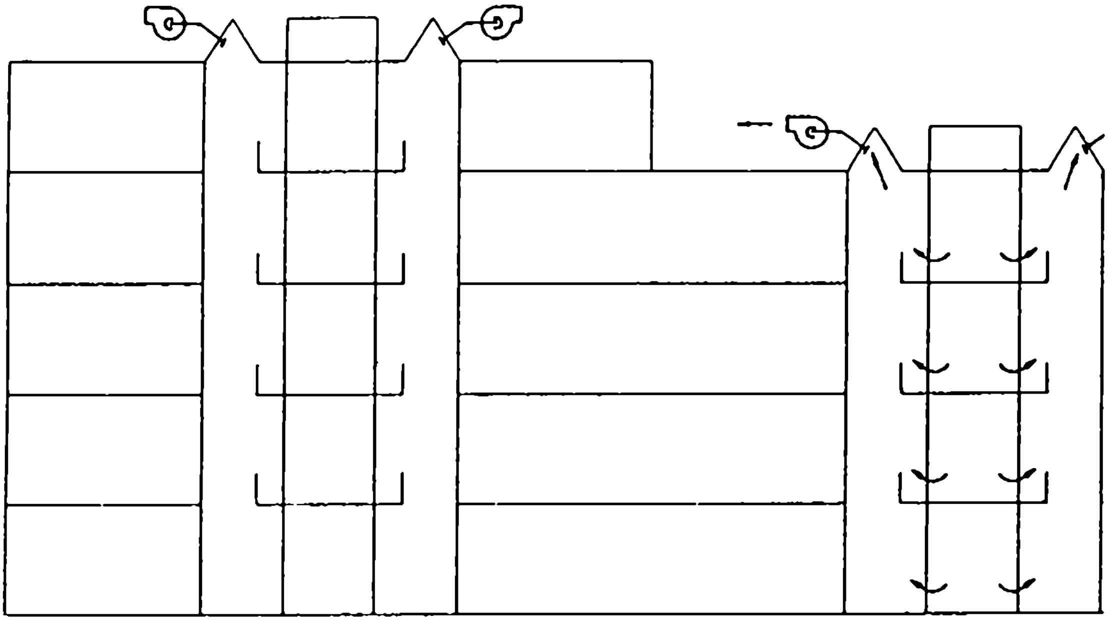

Figure 5: A Typical Multi Zone Network

One problem with this technique is that the calculated air flows are assumed to be constant for the simulation time step. When there are large openings, buoyancy driven exchanges can result in very large heat flows. If the simulation time step is too large, the constant heat flow may significantly effect the temperature distribution, so the air flows may even reverse. In reality the temperatures will reduce as the temperatures equalise, but as the programs are run independently, this effect cannot be handled effectively.

6.5.3 Full Integration

This method involves the explicit solution of the air flow equations as part of the overall simulation. Thermal simulation programs set up a series of equations defining the energy balance of each space. These are solved using a variety of solution methods. Full integration of the air flow requires that the equations that describing the zonal air flows are incorporated within the matrix covering all the other heat transfer processes, and solved simultaneously.

6.6 Computational fluid dynamics (CFD)

More recently, attempts have been made to incorporate computational fluid dynamics codes (CFD) into thermal models.

When attempting to model the air flow patterns in large spaces, the application of multi zone techniques can present a few drawbacks. Multi zone assume that all the air in each zone is fully mixed. This requires that stratified spaces be subdivided into a number of coupled zones. The basis for such subdivision requires considerable expertise and experience. Work has been carried out on the optimisation of the zonal patterns for atria.

A CFD code uses numerical methods to solve the basic equations describing the conservation of mass, momentum and heat in fluids. First the volume of interest (such as a room) is divided up into a large number of small cells, also known as the grid. The generation of the grid is perhaps the most important stage of the setting up of the CFD code and will take typically 80% of the preparation time (Fawcett 1991). This is because the number and distribution of grid cells can effect whether a solution is obtained, the speed at which it is obtained and the accuracy of the simulation. With the aid of fluid physical property information and the boundary conditions (eg. inlets/outlets, flow rates etc.) the conservation equations are solved to give typically, three components of the velocity, temperature and pressure for each cell in the grid.

The solution is found by iteration. That is the values of all the variables (velocity, pressure etc) are estimated. These values are then updated by feeding them into the equations which you are trying to solve. If the updated values are the same as the previous values, perhaps to a desired tolerance, then the solution is said to have converged.

The technique has limitations in terms of how accurately it can simulate what is happening in the real world. These limitations are generally caused by one or both of two aspects: the formulation of the grid, and the mathematical representation of air flow and turbulence, especially for inlets and outlets. Further details are given by the AIVC Technical Note 33 (Liddament 1991).

One of the problems of CFD is to properly describe the boundary conditions of surface temperature, surface heat fluxes etc. This is particularly important where natural convection is dominant. Thermal models can be used to predict these values, and so the thermal and CFD models can be run sequentially, much as described in section 6.5.2. However, because of the very large run times of the CFD method, the models are only likely to be used in tandem to investigate a single 'snap shot' in time rather than any extended period. Another problem is that in the main, thermal models produce surface average temperatures for input to the CFD code. It is local 'hot spots' from solar patches falling onto a floor or wall which generate the convection currents, and the strength of this effect may be minimised by surface averaging.

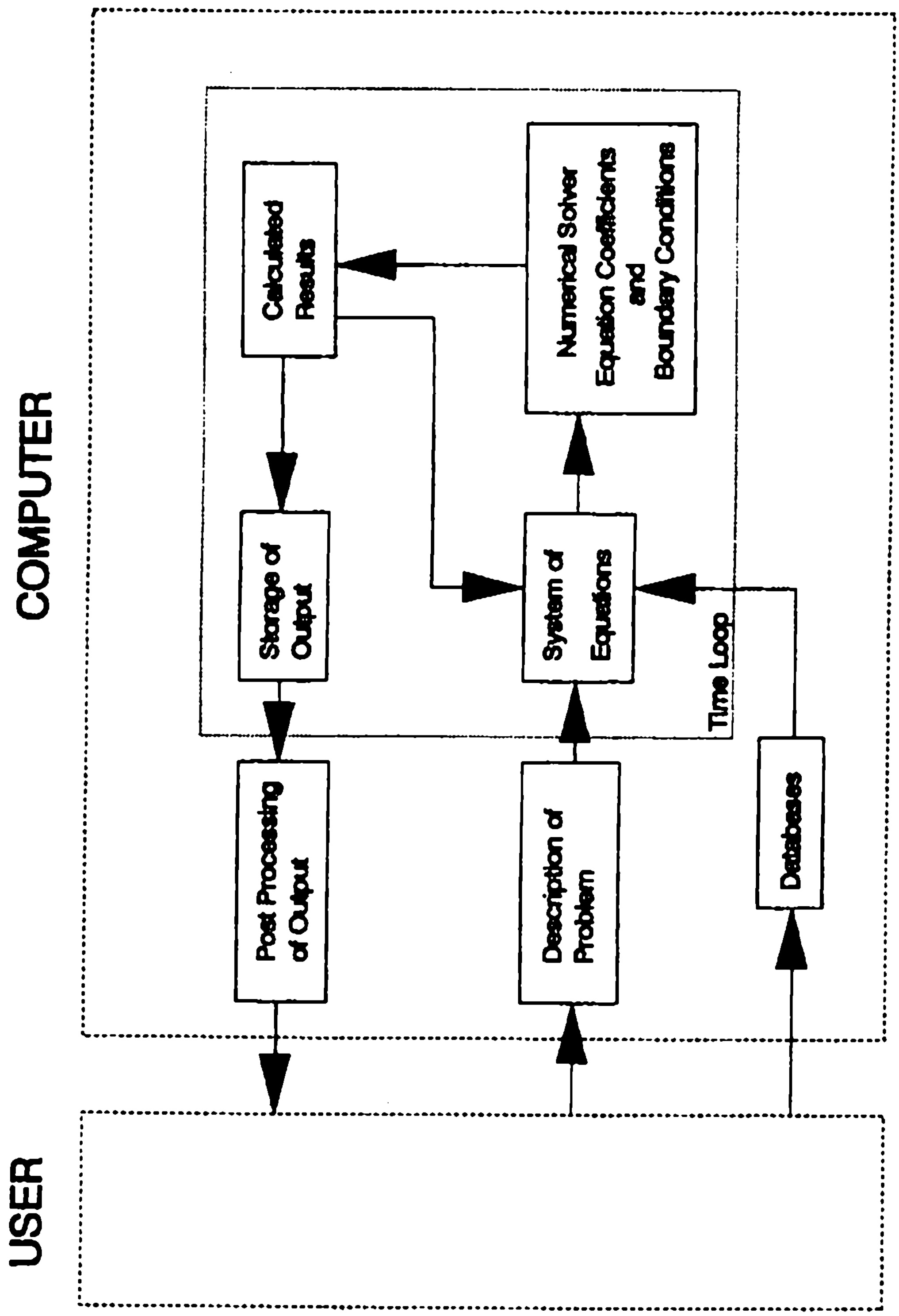

Figure 6: A simplified computer representation

7 Relevant Parameters

As the codes become more complex, the data required to take full advantage of the simulations also becomes more detailed. The conventional sources of information are often not presented in a suitable form, or even contain the required information to a sufficient degree of accuracy. These data may require additional editing to be suitable for a particular code. Data may be available in recognised forms (Harrje and Piggins, AIVC 1991), or as the result of independent research. The level of input detail for the computer model will depend on the nature of the problem to be investigated.

Climate

Data sets for the numerical prediction of the local climate are often derived from measured values. These sets of data are frequently taken at a remote site eg. weather station or airport, so extrapolation of the information is required to be applicable to the desired building location. Local climatic information is essential for an accurate prediction of the pressures, wind distribution and temperatures surrounding a building. This information is critical in the prediction of the internal climate of a building.

Terrain

The local terrain will have an influence on the climatic conditions experienced by the building. Shelter offered by other buildings as well as natural obstacles will influence the shape and turbulence parameters of the atmospheric boundary layer (Walker 1992).

Building Design, Materials and Properties

This would require a data set containing a selection of materials data, and would demonstrate the variability of the data available. The accuracy of computation is now far greater than the tolerances and uniformity of building materials and constructions, or the methods of describing (coding or 'inputting') the building fabric for the purposes of computation. As most of simulation programs are complex, there is a large gulf between the sophisticated computational methods and everyday practice of the architect who will often use simplified methods.

Leakage Data

The prediction and measurement of leakage paths and the air flow patterns created, is dependent on the experience of the user. It is impossible to predict all the potential flows due to cracks within the building fabric. Values of leakage data can be obtained from various experimental techniques described by Charlesworth (AIVC 1988).

The AIVC's numerical database will contain information in this area in a form that will be used for a range of building applications.

Wind pressure coefficients

Wall averaged values of Cp usually do not meet the accuracy required for air flow calculations. More detailed evaluations, taking into account the Cp distribution on the envelope of the buildings, can be made in different ways: Performing full scale measurements when an existing building is being studied, carrying out wind tunnel tests on models of existing or designed buildings, generating Cp values by 3-dimensional numerical air flow models or generating Cp values by numerical models based on parametric analysis of wind tunnel tests.

The AIVC's numerical database will contain information in this area in a form that will be used for a range of building applications.

HVAC Design

A number of factors relating to HVAC equipment selection can have an important influence on the overall energy balance of a space. For example, the radiant/convective proportions of heat being given out by a heat emitter can vary significantly from a high temperature radiant panel through to a convector. This can have a very significant impact on energy use in areas of high air change rates.

The internal flow patterns and temperature distributions are dependent on the design and operation of the heating, ventilation, and air conditioning system. The modelling of diffusers and nozzles is complex as the turbulence parameters required in the simulation of wall jets and wall thermal constants are difficult to predict (Whittle 1991).

Occupancy

Annex 8 (Dubrul 1988), Inhabitant behaviour with respect to ventilation, concluded that:

- ventilation behaviour (its frequency, duration and motives) is related to the type of room in which it occurs;

- differences, between households, in patterns of ventilation behaviour appear to be expressed in the form of the differences in the types of strategy used to control the indoor environment, (its temperature, air quality and the presence of external noise,) in relation to the indoor environment;

- ventilation behaviour is highly weather dependent but its dependency varies by the type of room, and also differences occur between occupants on the perception of temperature differences;

- ventilation behaviour is influenced by the design characteristics of the building and its heating/cooling system. This can effect the needs of the occupants and make ventilation easy to accomplish.

Internal Sources

Internal sources of heat and/or pollutants can influence the air flow patterns within a building. Buoyancy effects can be difficult to model accurately as they often call for assumptions within the calculations. Heat sources are common in the office and factory environment, with the frequent use of personal computers and work stations. The movement of contaminants within the design area can be a critical aspect of the simulation, particularly with the prediction of smoke movement within occupied areas.

8 Review of Some Air Flow/Heat Transport Models

Thermal Analysis Research Program (TARP)

TARP was developed by Walton (1982, 1984) as a research tool for the thermal analysis of buildings, with the aim to study the complex interactions of the heat transfer phenomena. The code uses a heat balance method for the simultaneous calculation of the heat loads of multiple rooms. Inter room conduction and convection processes are studied in detail. The code is written in Fortran to run on a mainframe computer system. Features that would have enhanced the code for the usability of the program for building designers and engineers have given way to research features. In its present form it is capable of calculating room loads and temperatures by simultaneously considering conduction and air movements between all rooms in a building.

The three modes of heat transfer are modelled as follows:

Conduction: Transient conduction effects are modelled by 'conduction transfer functions' which are developments of the response factors of the building envelope. They model the heat storage effect of the walls, furnishings and the partitions between rooms. Movable insulation is closely approximated by a massless insulation model with appropriate controls which may be applied to areas of windows and walls.

Radiation: The transmittance and absorption of the windows is computed from the optical properties of the window panes. The shadowing and distribution of sunlight on surfaces may be calculated in several levels of detail up to the amount of light transmitted through the windows onto each surface in the room. Emissivity is modelled for both interior and exterior surfaces. A simple model is applied to account for the potential energy savings of daylighting.

Convection: The program uses variable interior and exterior convection coefficients as functions of the temperature difference and the system induced flow velocity where appropriate to the calculation. It can compute the flow of air between rooms caused by wind and thermal forces. This is achieved by incorporating the multi zone algorithm AIRNET (Walton 1989). There is an alternative simple method for infiltration with options of ventilation cooling, a whole house fan, and controlled air mixing between two rooms.

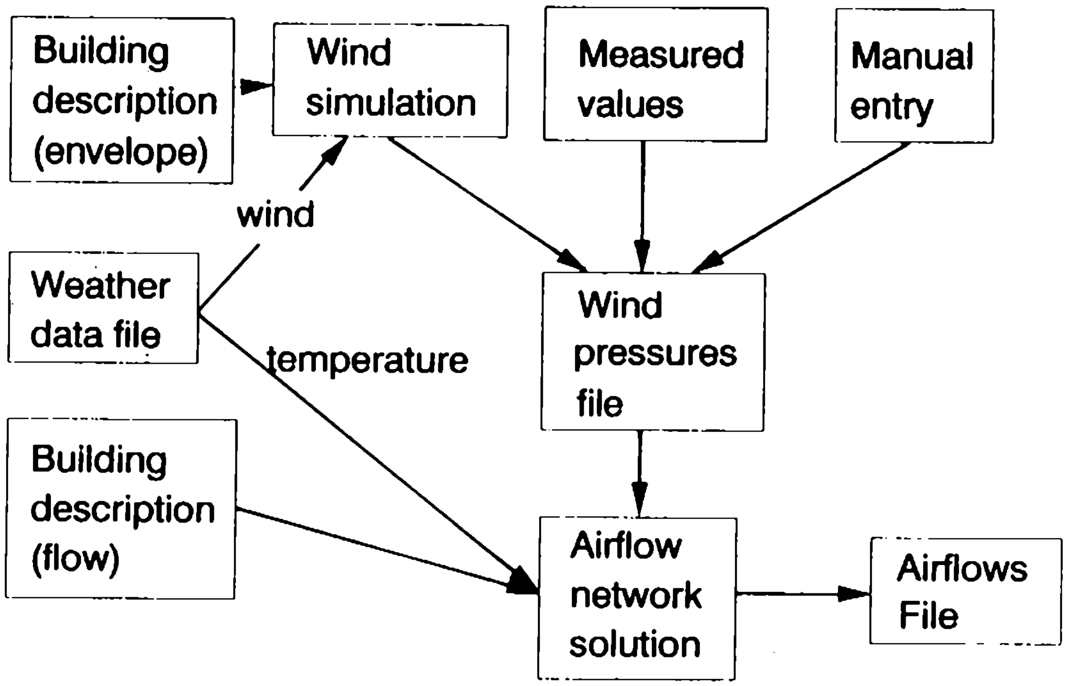

Figure 7: Structure of the air flow program, AIRNET

FEMALP, Modelling heat, moisture and contaminant transport

Finite Element Method Application Language Program (FEMALP) is a development of the above multi zone Thermal Analysis Research Program, TARP. This software was developed by Florida Solar Energy Center (Kerestecioglu et al 1989) to model the problems of combined heat and moisture transport. The software allows the user to perform heat and moisture transfer simulations at different levels of detail. A building is described as being composed of several solid and air interfaces. The solids may consist of the envelope, internal walls or furniture and the air may be indoor or outdoor air. There are many simulation options available, these include:

(i) Distributed heat and moisture transfer calculations for solid and air domains. Both the solid and the air domains are discretised and the problem is solved as a continuum. This option requires the solution of the flow equations or the detailed description of the flow field.

(ii) Distributed heat and moisture calculations for solid domains exposed to user defined boundary conditions. The user can specify the convective boundary conditions.

With this option the performance of a single structure can be investigated independently.

(iii) The addition of the ability to calculate the associated loads on the internal structure and configuration of the building. Tests have been carried out with the code to calculate the problems associated with natural convection in a square cavity. The data produced compared well with test data from the calculation of heat and mass transfer in attic spaces and a typical wood frame wall.

This code has been successfully applied to a variety of problems but the preparation of the input files are described as tedious. The current version requires users with an extensive numerical analysis background. Version 2 will be available in the future for users with less experience in the mathematics of the problems. FEMALP runs on a VAX mainframe system.

ESP, Environmental Systems Performance, ESPAIR and ARIA.

The program ESP is built up of program modules (Clarke 1987). The module ESPsim uses a numerical method to integrate the various equation types which are used to represent heat and mass balances within a building or plant network. The program is non-building type specific and is aimed at handling any building geometry, construction and operation. The system offers a way to analyse the energy performance of a building and its environmental control system. For each observable energy flow path in a building, ESP has a corresponding mathematical model. Within a simulation, a special numerical technique ensures that all flow paths evolve simultaneously to preserve the important spatial and temporal relationships. ESP will accept some building or plant description in terms of 3-D geometry, construction, usage and control. This continuous system is then discretised by division into small finite volumes of space, perhaps as many as 10,000 for a medium sized building. These finite volumes represent the various regions of the buildings and plant within and between which energy and mass can be exchanged.

Throughout the subsequent simulation, ESP tracks the energy and mass balance for all finite volumes as they evolve under the influence of the system boundary conditions and any constraints imposed on the inter-volume links. The technique ensures that all regions of the building are correctly connected across space and time so that any excitation at some point in space or time will have the correct causal effect.

The two largest modules ESPsim and ESPout require the most memory, about 1.5 Mbytes of memory each at run time, so the ESP system is set up for use on two kinds of machine: 1. A VAX series 11/750 or 11/780 running VMS 2. Any system running the UNIX operating system, ie a work station.

The thermal problems involved in a simulation are dealt with in the following ways:

Transient Conduction.

The assumption is made that conduction is uni-directional. Four conservation equation types are available to represent the transient conduction in multi-layered constructions. These are for homogeneous volume, heterogeneous volume, a cavity volume and a cavity/homogeneous volume. It is also possible for construction elements to be transparent so that shortwave flux can be internally absorbed. Conduction is a function of; conductivity, density, specific heat, dimensions, cavity long wave radiation, cavity ventilation and internal heat generation.

Convection Coefficients.

These are computed, for each surface (internal and external) at each time step, from buoyancy correlations. For internal surfaces, the coefficients are a function of the surface temperature, adjacent air temperature, aspect and direction of heat flow and the characteristic dimension. For external surfaces the values relating to wind speed and wind direction are important. It is also possible to substitute user-specific values for any of the surfaces at any time within a simulation.

Internal Longwave Radiation

Three algorithms are available for use within ESPsim to compute the net longwave flux exchange between surfaces at each time step.

The first is an analytical approach which determines a linearised radiation coefficient for all combined surfaces. These coefficients are then inserted in the system matrix equation to influence the simultaneous solution. This is the default algorithm.

The second establishes a zone radiosity matrix, a description of the rate at which radiation leaves surfaces. This is then inverted at each time step to give the net heat flux gain or loss at each surface, based on the latest surface temperature data, which are then applied as excitations to the system matrix equation.

The third is a recursive ray tracing technique which also establishes the net flux gain or loss to each surface based on the latest surface temperature data. In each case the calculation depends on the surface temperature, surface emissivity and the inter-surface view factors.

Airflow is automatically incorporated into the ESP using the multizone code ESPAIR (Clarke and Hensen 1990). As an alternative a more detailed simulation is possible by combining ESP and the ARIA code (Awbi 1990, Setrakian and McLean 1991). Work has been carried out to provide these boundary conditions for the CFD code ARIA developed by Awbi (1990), using the building simulation code ESP. This technique has been applied to particular case studies to predict the infiltration rate and solar gain, and their effect on the air flow patterns and temperature inside an atrium, and the effect of concentrated heat inside a clean room.

ESP employs a finite volume and heat balance technique which enables a high degree of insight into the energy flow processes within a building (Clarke 1985). This allows a greater understanding of the interrelation between design and performance parameters, which may be applied to identify problem areas, and to implement and test appropriate building, plant and/or control modifications.

Typically the procedure for the interactive running of ESP and ARIA is as follows:

1. ESP is used to simulate the problem with account taken for all the air leakage points including dynamic opening and closing of these elements eg. doors and windows. With ESP it is possible to identify the critical occurrences of either occupant discomfort, are air movement characteristics for a particular design problem.

2. Having then decided on the time that a more detailed design study is required of the problem the following information is obtained from ESP and used as boundary conditions for ARIA:

- Temperature at each surface of the ESP model

- Air volume flow rates into and out of each external opening of the model eg. doors and windows

- Bulk air temperatures ie. temperature of each ESP zone

- Mechanical supply and extract rates at the appropriate instant in time

The addition of intelligent front ends to aid the user (McRandall 1987) in their choice of application and aid the user in the creation of the essential boundary conditions for the use of the code. Further developments are taking place such as the Energy Kernel System (EKS) (Clarke 1987), and the addition of advanced drafting techniques to create video representations of the information produced from the code (Setrakian et al 1991). The modelling of various environmental aspects such as solar gains on the building envelope can be simulated. A research version is being used for the prediction of the coupling of heat and mass flow (Hensen and Clarke 1991).

R2D2 and AIRFLO, also the development of ROOM

Holmes (1990) approached the problem by directly combining of the capabilities of the dynamic thermal model with a CFD code, AIRFLO (Holmes et al 1990). The dynamic thermal model in this survey used in the exercise has a two-dimensional version of a general model, ROOM, developed by Arup R&D (Holmes et al 1990, Holmes and Whittle 1987). The two-dimensional model has the following characteristics:

Explicit finite difference algorithm. Long wave radiant interchange by means of a linearised radiosity model. Transmitted, direct short wave radiation is distributed onto surface elements according to solar and element priorities. All shortwave reflections are non-specular, and dealt with via the radiosity concept using short wave absorption coefficients. A single pane of glass has two nodes, one at each surface, solar radiation is absorbed at the nodes and the thermal capacity of the glass is also located there - so glass is modelled as a node network with heat input at both nodes.

The basic algorithm for R2D2 (ROOM version 2, 2-dimensions), after reading in all data, is:

- Calculate radiation form factors.

- Set up and invert long wave radiosity (the rate at which radiation leaves a surface) matrix.

- Set up and invert short wave radiosity matrix.

- Assume an initial internal air temperature and calculate the heat transfer temperatures for each surface element.

- Calculate the model temperatures within all fabric elements using the basic forward-difference equation.

- Obtain surface temperatures and hence air temperatures by either assuming a fully mixed space, or by transferring surface temperatures to the air flow model, AIRFLO.

- Calculated transmitted and absorbed solar radiation, and the internal distribution of radiation, then return to the addition of the air temperature using the new calculated values.

Typical time steps for the analysis are 30 seconds, the limit being the time constant for the glazing. The convective heat transfer coefficient is taken as constant. For a typical calculation the codes require the use of a SUN SPARCstation using 403 minutes of cpu time for the fully coupled case.

DTAM1, Discrete Thermal Analysis Method

The Airflow Network Analysis Method (Axley and Grot 1989, 1990) and the Discrete Thermal Analysis Method allow a fully integrated approach to the modelling of the building envelope, construction and the heating and ventilation system.

In its application to building thermal analysis, the element assembly approach is based on the idea that building thermal systems may be idealised by the assembly of discrete thermal elements chosen to model specific instances or aspects of thermal transport that occur within the building system. The program DTAM1 has been developed to demonstrate a basic approach, by providing five thermal elements including a simple thermal resistance element and a well mixed zone or lumped capacitance element, a fluid loop element, and 1D and 2D conduction elements based on isoparametric finite element formulations.

The assembly operation of the elements is described formally by Axley and Grot (1990) and provides a mathematically rigorous definition that is useful for theoretical analysis and development. It is a computationally inefficient strategy for the assembly, so more direct computational algorithms are used in practice. Application of this system of equations to problems in practice, temperature conditions have to be accounted for. Considerations of temperature boundary conditions and zero capacitance nodes become key issues when developing the computational strategies for this approach.

The building air flow system is idealised by an assembly of flow elements that model the pressure flow characteristics of discrete flow paths in the building or the HVAC system. Flow element equations are formulated and, for each specific system idealisation, element equations are assembled to form the system equations.

The thermal equations may be used to determine the thermal response of a building system. The steady air flow equations are adopted to formulate a system of equations that describe the dynamic air flow analysis problem. These equations are then integrated with the dynamic thermal analysis equations to form a system of equations that describe the coupled problem.

CLIM 2000

CLIM 2000 is a modular software system development of Electricit de France (Gautier et al 1991) in 1985. It is a research tool designed for a broad range of applications such as the detailed analysis of comfort and heat exchanges, development of control and building energy management systems, energy and financial evaluation of different projects.

The air movement inside a room is described using the code SAMIRA (Simulation Araulique des Movements Intrazones en Rgime Anisotherme). This multizone model is based on the drafting of mass and energy balance equations for each area. Inter area mass transfers are computed using Bernoulli's equation assuming that there the velocity in each area is zero. Therefore no quantity equations are available for movements, which involves the assumption that all the kinetic energy is entirely dissipated by turbulence within each area. This simplified modelling of the air flow will be integrated into the heat software CLIM 2000 (Bouia and Dalicieux 1991).

The experimental results of the running of SAMIRA have shown that air movements and temperature gradients within rooms can be represented with the use of a simplified model ie. SAMIRA. Tests have shown that tests performed under standard pressure are not sufficient since the absence of representation of dynamic areas such as jets and plumes does not enable the full description of inter-area flow and also the temperature distribution. Validation has continued with the comparison of the tests results with scale and full size models. The integration of SAMIRA with the global software program CLIM 2000 will then enable the representation of the coupling of air flow with various thermal phenomena and to carry out extensive evaluation surveys of the comfort provided within a heated dwelling room.

ROOM-CHT, building energy calculations.

The ROOM-CHT, which was developed by Hammond (1986) describes the flow and thermal field within mechanically-ventilated enclosures using the known characteristics of turbulent wall jets. These jets are the normal means of air distribution in a building with forced convective heating or cooling systems. The code was developed for both two- and three-dimensions, to allow the modelling of ventilation systems in rooms with supply divides of either slots of rectangular grilles. The mean flow properties for the three-dimensional version used are calculated from wall jet empirical data. These are then employed to determine the corresponding local heat transfer distribution over the room surfaces.

In its present form ROOM-CHT is only valid for air distribution systems where the supply air is emitted near, and runs parallel to, one of the room surfaces. This is not regarded as a major problem as the designer is usually faced with the problems of input-specific data. One inherent problem of the intermediate code (Hammond 1988) is that because it is a generalisation of a simple code it cannot predict the effects of complex flow interactions.

PHOENICS and ACCURACY

The combination of an air flow model and a thermal load program is continued with the combination of the two codes PHOENICS and ACCURACY, A Cooling-load Code Using Room Air Currents (Chen et al 1988). The air flow program PHOENICS is used to study the three-dimensional air velocity, air temperature, turbulent energy, and contaminant concentration in the room. The thermal load program ACCURACY provides thermal boundary conditions for the air flow program PHOENICS.

PHOENICS is a commercial air flow program developed by Launder and Spalding (1973). The computational method involves the solution of three-dimensional equations for the conservation of mass, momentum, energy, concentration, turbulence energy and the dissipation rate of kinetic energy, with wall functions used to described the addition of solid boundary conditions. In order to produce the boundary conditions for PHOENICS, the thermal load program ACCURACY is used.

ACCURACY is based on the room energy balance equation method and can consider the influence of room air temperature distribution. Ideally the flow code PHOENICS would provide the temperature differences for the code ACCURACY at hourly intervals. But the K- model becomes an expensive choice for updating the time dependent temperature and air flow distributions due to the size of grid required. There is no repeated interaction between ACCURACY and PHOENICS, the temperature conditions are set for the thermal code by the air flow model. It can also be applied to the prediction of the transient behaviour of contaminants in the flow region.

ACCURACY calculates the radiative heat exchange between the room enclosure surfaces, the transient heat conduction into those surfaces and determines the enclosure surface temperatures and air-conditioning loads. The convective heat exchange between heat sources and the room air can be calculated in ACCURACY and then inserted in the air flow program PHOENICS as a thermal source.

The combination of the two codes is applied to a variety of problems involving the heating and ventilation of a room and the comparison of the calculated results with experimental data (Chen et al 1988).

TFCD

The program TFCD (Temperature, air Flows, Concentrations of contaminant and air quality in terms of predicted percentage of Dissatisfied due to contaminant concentration) has been developed at Helsinki University of Technology (Klobut et al 1991). The source code of the program is Fortran 77 (Klobut 1991) and is designed to operate on a microcomputer in only one or two days.

The simulated building is modelled by a multizone network whose branches represent air flow routes and its nodes refer to the volumes or zones. The program is capable of simulating a system consisting of almost 40 nodes. In order to enable the simulation to represent realistic situations, the following options are provided for use in the program:

- outdoor air temperature - constant, changing according to a sine function in a 24 hour period or changing stepwise with a free schedule.

- barometric pressure, wind speed and direction - constant or changing freely.

- supply air temperature of mechanical ventilation - constant, changing stepwise with a free schedule, equal too outdoor air temperature, equal to the temperature of a mixture of outdoor air and return air.

- thermal loads by convection and radiation - constant, changing stepwise with a free schedule.

- strengths of contaminant sources - constant, changing stepwise with a free schedule.

- type and pressure-flow characteristics of air flow routes - constant, changing with a free schedule.

Each room in the building is considered as one or more zones vertically stacked. One network node is placed in each zone and it is assumed that the air inside the zone is instantly and perfectly mixed.

The thermal capacity of the zone air is calculated at each time step but the thermal capacity of the wall is approximated by one constant. The Euler method is used for solving the temperatures. Advantages of this are the minimal computational time required to find temperatures and the fact that there is no need for any interaction between the temperatures and the air flows.

9 Conclusions and Future Work

There are many methods available to simulate room air movement and heat transfer. Developments to incorporate intelligent front ends into the recent crop of models will mean that the codes will become available to a wider field of operatives.

The future integration of Computer Aided Design (CAD) packages to enable the designer create a building, then use the model to simulate the flow parameters is essential. Using the initial drawing along with a comprehensive library of information about the behaviour of the construction and properties of the building fabric (Setrakian and McLean 1991) will enable a single designer to create and simulate conditions within the design. The development of user friendly front ends for programs will promote their wider use within the design field, appealing to the architect and the building services designer.

Previous design restrictions, are being removed with the increased computing power available today at reasonable cost to the user and the increase in the background knowledge of the user in all aspects of the design phases. Then the application of menu driven and request driven information translators will speed the design process further. Emslie (1991) proposes the use of intelligent front ends and video graphics to 'animate' the final product which will increase the use of these tools in the everyday environment.

When dealing with multi-cell, it is increasingly popular to subdivide the large areas of concern (atria) into smaller cells, for a general flow regime. In this case it may be possible to combine these results with other computational techniques such as CFD to give a full view of the thermal response and the air flow patterns.

Many advances are taking place in the development of solution techniques and discretisation systems. In some cases these advances make further demands on the hardware systems employed.

Further development of the fully iterative approach for the interactive coupling of air flow and thermal analysis of a building will increase the practical use of the simulation techniques. With the increase in computing power for less cost the fully interactive method will be computationally and financially viable in the near future.

A comprehensive program of validation and evaluation is required for the further development of the codes in the design field. Work has been carried out on the application of benchmark tests and some work has been completed on the comparison of simulation with scale models. These tests should be applied to the models to evaluate their performance. The benefits of these advances need to be assessed as part of an independent validation study. A sensitivity analysis of parameters is required so that key parameters can be identified (Oldengarm 1990) and incorporated into simplified methods. Many of these items have been addressed by the IEA Annex 20 'Air Flow Within Buildings' (Moser 1989,1991) and by ASHRAE Research Project 464 'Calculation of Room Air Motion' (Baker and Kelso 1990).

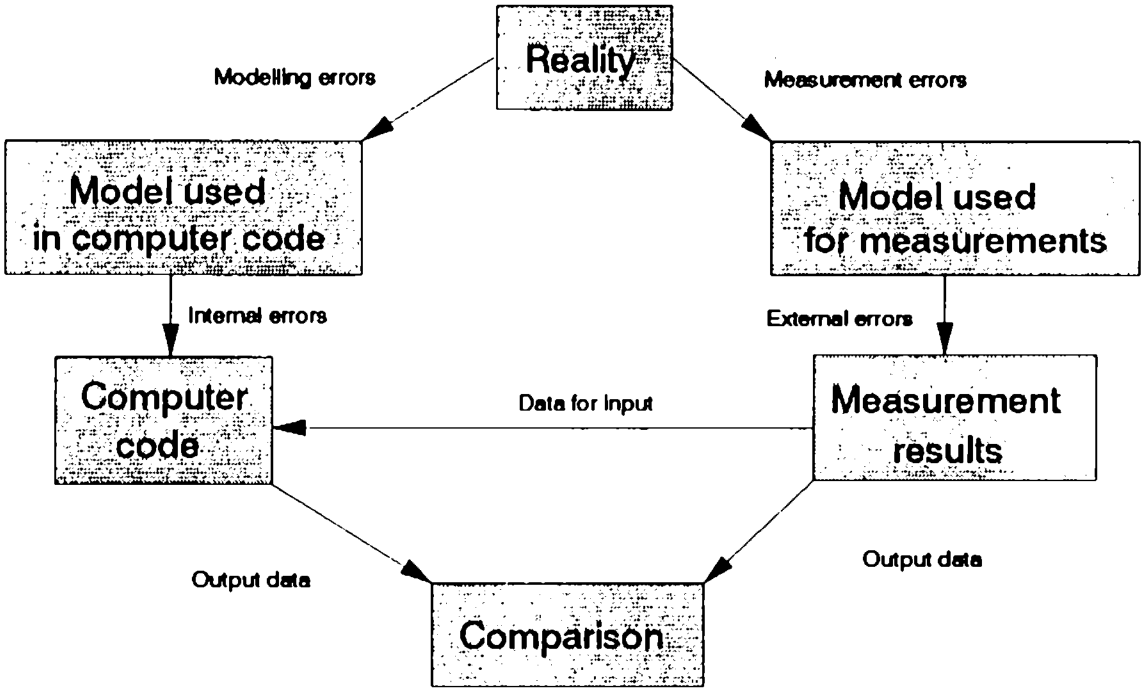

Figure 8: The Stages Required in Modelling Reality

To support design work a numerical database is also needed. Developments of parts of such a database is taking place at the Air Infiltration and Ventilation Centre.

References

#NO 2289 Computation of air flow and convective heat transfer within space-conditioned, rectangular enclosures.
AUTHOR Alamdari F, Hammond G P, Mohammad W S
BIBINF Proceedings of the Fifth International Symposium on the use of computers for environmental engineering related to buildings, Bath, 7-9 July 1986, CIBSE 1986, p191-205, 4 figs, 4 tabs, 32 refs.
#DATE 00:07:1986 in English AIVC bk
ABSTRACT In order to obtain means for determining realistic convective heat transfer coefficients, a hierarchy of interacting and interdependent calculation methods have been developed by the authors. Both higher and lower level models have been used to develop and verify an 'intermediate level' computer code, which formed the basis for generating input convective heat transfer data for dynamic building models. The contribution considers the computation of convective heat exchange within three-

dimensional, rectangular enclosures when buoyancy effects are significant. It attempts to evaluate the circumstances under which it is appropriate to employ the various calculation methods.
KEYWORDS computer, convection, heat transfer, air flow, calculation techniques

#NO 5227 Annex XIV, Condensation and energy, Sourcebook.
AUTHOR Anon
BIBINF IEA Energy Conservation in Buildings and Community Systems, Annex XIV: Condensation and Energy, Final Report, Volume 1, March 1991. #DATE 00:03:1991 in English
ABSTRACT The idea to start an Annex on mould, surface condensation and energy grew in 1984-1985. In September 1985, a workshop was organised at the Leuven University, Belgium, focusing on the state of the art in different countries. This workshop revealed a real lack of overall knowledge and understanding, on the levels of data, modelling and measuring. The Annex objectives were formulated as: - providing architects, building owners and practitioners as well as researchers with a better knowledge and understanding of the physical backgrounds of mould and surface condensation, including the critical conditions for mould growth and influencing material properties; - to introduce better calculation models, taking into account air, heat and moisture transfer, in order to predict properly the phenomena of mould and surface condensation and to validate possible solutions; - to develop energy conserving and cost effective strategies and complementary design methods, techniques and data for avoiding mould and surface condensation in new buildings or preventing further degradation in problem buildings.
KEYWORDS condensation, energy consumption

#NO 4126 The role of numerical solutions in room air distribution design.
AUTHOR Awbi H B
BIBINF Norway, Oslo, Norsk VVS, Roomvent 90, Proceedings, 13-15 June 1990, paper 2, 11 figs, 12 refs. DATE 00:06:1990 in English

ABSTRACT A Computational Fluid Dynamics program called ARIA developed by the author and his colleagues is applied to predict the flow in wall jets and in rooms for isothermal and non-isothermal situations. The diffusion of two- and three-dimensional wall jets with and without wall obstructions was numerically predicted and the results were corroboratedwith measurements in an air jet test facility. A two-dimensional solution was used to predict the isothermal and non-isothermal flow in a room supplied with a cold jet from a linear ceiling diffuser. The effect of downdraught from the glazed walls of a room heated with a low-level upward displacement system was also predicted using three-dimensional solution.
KEYWORDS numerical modelling, air distribution, design

#NO 3536 The coupled airflow and thermal analysis problem in building air flow system simulation.
AUTHOR Axley J, Grot R

BIBINF Preprint, Ashrae Trans, Vol 95, Pt, 1989, 8pp, 1 fig, 16 refs. #DATE 00:00:1989 in English

ABSTRACT The Indoor Air Quality and Ventilation Group at the National Institute for Standards and Technology (NIST, formerly the National Bureau of Standards) has developed a method of building airflow analysis, based upon element assembly techniques, that has been successfully applied to the determination of the macroscopic characteristics of infiltration, exfiltration, and interzonal airflows in complex building airflow systems driven by wind pressures, buoyant forces, and the building HVAC system. This analytical method was formulated to be compatible with a discrete thermal analysis method, also based on element assembly techniques and developed earlier, which may be applied to problems of building thermal analysis. This paper will review the theoretical bases of these two related methods and present a theoretical framework to solve the coupled airflow and thermal analysis problem in building airflow system simulation. Formulation of the coupled airflow-thermal analysis problem will be presented and numerical methods for the solution of this problem will be outlined.

KEYWORDS air flow, simulation, thermal analysis

#NO 4131 Coupled airflow and thermal analysis for building system simulation by element assembly techniques.

AUTHOR Axley J, Grot R

BIBINF Norway, Oslo, Norsk VVS, Roomvent 90, proceedings, 13-15 June 1990, paper 7, 15 pp, 3 figs, 23 refs. #DATE 00:06:1990 in English

ABSTRACT Element assembly techniques have been applied to developed methods to model a) airflows driven by wind pressures, buoyant forces, and HVAC systems and b) heat transfer due to conduction, convection, advection, and radiation in complex multi-zone building systems. These methods, the Airflow Network Analysis Method and the Discrete Thermal Analysis Method, allow an integrated consideration of the building envelope, construction, and HVAC system interaction in each area of analysis, are computationally non-demanding, and can be employed to model building systems of arbitrary complexity. This paper will consider the integration of these methods to solve the coupled airflow and thermal analysis problem in macroscopic (i.e., whole-building, multi-zone) building system simulation. The theoretical bases of these related methods will be reviewed and a framework for integrating these methods to solve the coupled airflow and thermal analysis problem in building system simulation will be presented. A general approach for solving the resulting coupled system of equations, based on Newton-Raphson techniques, and special cases derived from this approach will be outlined.

KEYWORDS air flow, thermal analysis, simulation

#NO 3712 On validation of computational fluid dynamics: procedures for room air motion prediction.

AUTHOR Baker A J, Kelso R M

BIBINF USA Preprint, ASHRAE Transactions, Vol.96, Part 1, 1990, 15pp, 9 figs, 15 refs. #DATE 00:00:1990 in English

ABSTRACT An ongoing ASHRAE research project seeks to identify and clarify key issues governing literate application of computer-based analytical methods for prediction of room air motion. The engineering field is termed "computational fluid dynamics", with the acronym "CFD" which is maturing rapidly, paced by the incredible growth of scientific computing hardware capacity. As with any emerging technology, the production of reliable predictions requires a full understanding of intrinsic details. This paper addresses issues promoting literate use of CFD for prediction of room air fluid/thermal flow fields.

KEYWORDS validation, air movement

#NO 5032 BEPAC Building Environmental Performance '91.

AUTHOR BEPAC

BIBINF UK, BEPAC, Building Environmental Performance BEP 91, held University of Kent, Canterbury 10-11 April 1991, 280pp. #DATE 00:04:1991 in English

ABSTRACT Proceedings includes papers as follows:

1. Next Generation Building Services Engineering Software: Opportunities for the Practitioner
2. Data Accuracy and Model Reliability
3. Building Environmental Simulation & the Building Design Process
4. The Integrated Building Design System
5. Use of a Building Emulator to Evaluate Control Strategies Implemented in Commercial BEMS
6. An Expert System for Building Energy Management
7. The Development of a Spread-Sheet Based Design Tool for the Selection of an Ice Storage System Coupled to a Building Refrigeration System
8. Thermal Behaviour of a Simple Building: Measurements in an Outdoor Test Cell
9. Modelling as an Aid in The Thermal Performance Assessment of Passive Solar Components
10. Computer Generated Analysis of the Daylight Performance of Internal Architectural Spaces
11. High Performance Glazing - What are the Limits?
12. Risk and Uncertainty in Environmental Prediction
13. The Development of the National Home Energy Rating
14. Bredem 8, A Monthly Calculation Method for Energy Use in Dwellings: Testing and Development
15. Human Factors in Residential Energy Consumption
16. Yardsticks for Assessing Low Energy House Designs
17. An Intelligent Front-End for Building Performance Appraisal
18. Evaluating Design Performance in an Integrated Modelling Environment
19. Direct Search Optimisation of HVAC Systems Design
20. The Effect of Computational Parameters on the Accuracy of Results from Detailed Thermal Simulation Programs

21. The Energy Kernel System: The Way Ahead?
22. Quality Assurance in Environmental Performance Modelling
23. Performance Assessment Methodology: Technical and Methodological Issues for Development
24. Developing & Proving Sensitivity Analysis Techniques for Thermal Models of Buildings
KEYWORDS building design, energy efficiency

#NO 5353 Simplified modelling of air movements inside dwelling room.
AUTHOR Bouia H, Dalicieux P
BIBINF France, Building Simulation '91 Conference, held 20-22 August 1991, Sophia-Antipolis, Nice, France, published by IBSPA (The International Building Performance Simulation Association), 1991, pp 106-110. #DATE 00:00:1991 in English
ABSTRACT The need for increasingly sharp modelling of building energy behaviour allowing comfort to be evaluated within a heated, ventilated dwelling room leads Electricite De France ADE Department to develop an air interior movement simulation model. This is a simplified modelling which it could be possible to integrate into a global building science-of-heat software programme (CLIM2000). The design principle is the division of the air volume of the room into areas for which mass and energy balances are computed. Room areas where air flows at very low velocities (standard areas) and dynamic areas such as thermal plumes or jets are processed separately. An example of computation made using the first version of the model ie prior to the integration of plume and jet, evidences the possibility of using simplified modelling to represent interior air movement.
KEYWORDS modelling, air movement
#NO 4938 Buildings and the environment.

AUTHOR Boxer L
BIBINF Air Infiltration Review, Vol 12, No 2, March 1991, pp 1-7, 5 figs. #DATE 00:03:1991 in English
ABSTRACT The following points are considered: 1) The evolution of government policies to save energy in buildings. 2) The forces influencing future policies.
KEYWORDS indoor air quality, review

#NO 5331 The U.S. EKS: advances in the SPANK-based Energy Kernel System.
AUTHOR Buhl F, Erdem E, Nataf J M, Winckelmann F C, Moshier M A, Sowell E F
BIBINF Belgium, Proceedings of the Third International Conference on System Simulation in Buildings, held 3-5 December 1990 in Liege, Belgium, published by University of Liege, Laboratory of Thermodynamics, 1991, pp 107-150. #DATE 00:00:1991 in English
ABSTRACT The Simulation Problem Analysis Kernel (SPANK) was originally described as a prototype Energy Kernel System in a paper presented at the Second International Conference of System Simulation in Buildings in 1986. Since that time, it has undergone several enhancements and has been integrated into a larger software system that may be more properly called a prototype Energy Kernel System for building

energy analysis, EKS/US. Among the enhancements is the capability to simulate dynamic problems. Also, symbolic manipulation techniques are now used to generate objects and macro objects from equations expressed as text. Currently underway is the development of a graphical user interface. Newer developments include a reevaluation of the semantics of dynamic problem definition, which will ultimately result in much greater generality in user specification of numerical methods. This paper reports on these developments and indicates directions for future EKS/US development.
KEYWORDS simulation, building design, modelling

#NO 3292 Air exchange rate and airtightness measurement techniques- an applications guide.
AUTHOR Charlesworth P S
BIBINF UK, AIVC Technical Guide 2, 1988 #DATE 00:00:1988 in English
ABSTRACT A loose-leaf handbook divided into seven chapters covering air change rate, interzonal airflow and building airtightness measurement techniques.
KEYWORDS measurement technique, air tightness

#NO 3845 Measurements and computations of ventilation efficiency and temperature efficiency in a ventilated room.
AUTHOR Chen Q, Van der Kooi J, Meyers A.
BIBINF UK, Energy and Buildings, No.12, 1988, pp85-99, 12 figs, 3 tabs, 7 refs. #DATE 00:00:1988 in English
ABSTRACT In order to improve the indoor air quality in a room and to save energy, the air movement and contamination distributions in the room with ventilation have been studied experimentally and numerically. The experiment is carried out in a full-scale climate room with different air supply systems, heat gains from the venetian blinds and ventilation rates. The measurements concern room airflow patterns and air temperature, velocity and contamination concentration fields, etc. The airflow computer program PHOENICS and the cooling load program ACCURACY have been applied for the numerical simulations. PHOENICS solves the conservation equations of air mass, momentum, energy, concentration, kinetic energy and dissipation rate of kinetic energy. ACCURACY, which considers the influence of room air temperature distributions, is employed for the determination of cooling load, wall surface temperatures and convective heat transfer on room enclosure surfaces, These are the boundary conditions required by PHOENICS. The agreements between the computations and the measurements are good. The ventilation efficiency and temperature efficiency which are used for evaluation of indoor air quality and energy consumption are reported for each case. Additional application of these computations to annual energy analysis is also discussed.
KEYWORDS air flow, ventilation efficiency

#NO 2656 A summary technical overview of the ESP System
AUTHOR Clarke J A

BIBINF ABACUS CAD Unit, Department of Architecture and Building Science, Faculty of Engineering, University of Strathclyde, Glasgow G4 ONG, UK, March 1987, 14p, 2 figs, 38 refs. #DATE 00:00:1987 in English
ABSTRACT This paper presents a summary technical overview of the ESP System. The modelling techniques used within ESP are summarised and the theories which underlie each algorithm are referenced. This document should therefore be read in conjunction with the user manual and other publications as given in the Appendix.
KEYWORDS calculation technique, computer, modelling

#NO 4869 An approach to the simulation of coupled heat and mass flow in buildings.
AUTHOR Clarke J A, Hensen J L M
BIBINF UK, AIVC 11th Conference, "Ventilation System Performance", held 18-21 September 1990, Belgirate, Italy, Proceedings published March 1990, Volume 2, pp 339-354, 3 figs, 5 tabs, refs. #DATE 00:03:1991 in English
ABSTRACT This paper describes the techniques used within the ESP system to represent and solve the heat and mass conservation equations relating to combined building and plant systems. In particular, it describes the equation-sets used to represent inter-zonal (building) and inter-component (plant) fluid flow and the method used for the integration of the non-linear heat and mass flow equations. By means of a case study, the application in a real design context is demonstrated.
KEYWORDS simulation, air flow, mathematical modelling

#NO 4880 ROOM: a method to predict thermal comfort at any point in a space.
AUTHOR Conner P A, Holmes M J
BIBINF UK, Chartered Institution of Building Services Engineers, 1991, CIBSE National Conference 1991, held at University of Kent, Canterbury, 7-9 April 1991, pp 519-535, 4 figs, 21 refs. #DATE 00:00:1991 in English
ABSTRACT The paper presents the theoretical background to an analytical tool, called ROOM, that is used by a large design practice to predict comfort conditions, and plot detailed comfort contours within a given space. ROOM is based on a thorough analysis of the radiant heat transfers that occur within a complex space linked to an explicit finite difference treatment of elements that store thermal energy. Airflow modelling is, at present, limited to simple single zone or two zone (stratified) space, with buoyancy driven ventilation as an option. The output can, however, be used as input to a computational fluid dynamics program, and an example is given in the paper.
KEYWORDS thermal comfort, computer prediction

#NO 3320 Inhabitants' behaviour with regard to ventilation.
AUTHOR Dubrul C
BIBINF UK, AIVC Technical Note 23, 1988. #DATE 00:00:1988 in English
ABSTRACT This report summarises the IEA Annex 8 Study into the behaviour of occupants with regard to ventilation. It assesses the extent to which the actions of occupants can be modified in order to minimise energy use yet maintain adequate indoor air quality. Chapters cover observational techniques, energy loss due to window

opening, reasons for window opening and the resultant energy savings from modified use of windows.
KEYWORDS occupant behaviour, energy conservation, indoor air quality, window opening

#NO 5704 Getting started with CFD.
AUTHOR Fawcett N S J
BIBINF UK, London, Institution of Mechanical Engineers, paper from a conference "Computational fluid dynamics - tool or toy?" held 26 November 1991, pp 1-4. #DATE 26:11:1991 in English
ABSTRACT The recent developments in low cost, high power computing have made the use of computational techniques for the solution of complex industrial flow problems a reality. The market for general purpose Computational Fluid Dynamics (CFD) programs has grown as a result and is extremely competitive. CFD still requires a large investment (both money and time) and therefore it is essential that newcomers familiarize themselves with the methods, the limitations and the jargon used if they are to avoid a costly mistake. This paper describes in outline the above issues and gives some guidelines to choosing hardware and software.
KEYWORDS computational fluid dynamics, air flow, heat transfer, numerical modelling

#NO 4994 A survey of air flow models for multizone structures.
AUTHOR Feustel H E, Dieris J
BIBINF USA, California, Lawrence Berkeley Laboratory, Applied Science Division, March 1991, 49pp, 2 figs, 1 tab, 27 refs. #DATE 00:03:1991 in English
ABSTRACT Air flow models are used to simulate the rates of incoming and outgoing air flows for a building with known leakage under given weather and shielding conditions. Additional information about the flow paths and air-mass flows inside the building can only be made by using multizone air flow models. In order to obtain more information on multizone air a literature review was performed in 1984 [1]. A second literature review and a questionnaire survey performed in 1989, revealed the existence of 50 multizone air flow models, all developed since 1966, two of which are still under development. All these programs use similar flow equations for crack flow, but differ in the versatility to describe the full range of flow phenomena and the algorithm provided for solving the set of nonlinear equations. This literature review has found that newer models are able to describe and simulate the ventilation systems and interrelation of mechanical and natural ventilation.
KEYWORDS air flow, modelling, multizone

#NO 5352 CLIM 2000: The building energy simulation tool and the modelling method.
AUTHOR Gautier B, Rongere F X, Bonneau D
BIBINF France, Building Simulation '91 Conference, held 20-22 August 1991, Sophia-Antipolis, Nice, France, published by IBSPA (The International Building Performance Simulation Association), 1991, pp 99-105. #DATE 00:00:1991 in English

ABSTRACT After presenting the main features of the CLIM 2000 software, we describe in this paper, the principles of the modelling method. The application of it is illustrated by an example: the air movement modelling in a building. In particular, we demonstrate its efficiency to facilitate the model design and the hypothesis management.
KEYWORDS simulation, modelling

#NO 3234 Modelling building airflow related phenomena.
AUTHOR Hammond G P
BIBINF Expanded version of a presentation made to the BEPAC Special Meeting held at the Polytechnic of Central London, on 14 June 1988, 16pp, 7 figs, 16 refs. #DATE 00:06:1988 in English
ABSTRACT A hierarchy of calculation methods is 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.
KEYWORDS modelling, air flow, calculation techniques

#NO 5332 A fluid flow network solver for integrated building and plant energy simulation.
AUTHOR Hensen J L M, Clarke J A
BIBINF Belgium, Proceedings of the Third International Conference on System Simulation in Buildings, held 3-5 December 1990 in Liege, Belgium, published by University of Liege, Laboratory of Thermodynamics, 1991, pp 151-170. #DATE 00:00:1991 in English
ABSTRACT This paper outlines the ESP approach to the simulation of coupled heat and mass flows in integrated building and plant systems. It describes the equation-sets used to represent inter-zonal (building) and inter-component (plant) fluid flow, the method used for the simultaneous solution of these non-linear equations, and the solution coupling of the heat and mass conservation equation-sets. By means of a case study, the application in a real building performance evaluation context is demonstrated.
KEYWORDS air flow, simulation, modelling

#NO 2673 How accurate are the predictions of complex air movement models?
AUTHOR Holmes M J, Whittle G E
BIBINF Bldg Serv Engng Res Tech, Vol 8, No 2, March 1987, p29-31, 7 refs. #DATE 00:03:1987 in English
ABSTRACT The validation of computer predictions of physical processes is still a topic of concern, particulary in relation to dynamic thermal simulation modelling. However,

far more complex computer programs are now being introduced into the Building Services Industry. These new programs solve the conservation and equations of momentum, energy and mass to simulate air movement in and around buildings. The validation task is potentially more difficult than that encountered to date. This paper discusses some of the problems associated with the application and validation of these codes and suggests how a user can ensure that the physical processes are being modelled realistically.
KEYWORDS prediction, air movement, model, validation

#NO 4141 Computation of conduction, convection and radiation in the perimeter zone of an office space.
AUTHOR Holmes M J, Lam J K W, Ruddick K G, Whittle G E
BIBINF Norway, Oslo, Norsk VVS, Roomvent 90, proceedings, 13-15 June 1990, paper 19, 16 pp, 8 figs, 2 tabs, 8 refs. #DATE 00:06:1990 in English
ABSTRACT To ensure a good quality thermal environment it may be necessary in HVAC design to carry out a detailed evaluation of environmental performance using simulation techniques. The tools used are generally the dynamic thermal model and the computational fluid dynamics (CFD) code. These tools are complementary, and this paper describes a study involving a full transient coupling of two such codes (R2D2 and AIRFLO). A test problem consisting of a West-facing perimeter office space with a ceiling-mounted diffuser was considered, and results are presented of simulation over a two hour period on a cold morning. Comparison has been made between full transient coupling and a sequential operation of the codes. The operation of the codes in coupled form highlighted a transient oscillatory behaviour of the air movement field resulting from the nature of the system and controller. The computational overhead of operating the dynamic thermal model was found to be 0.5% the run-time being dominated by the heavy computational requirements of the transient CFD analysis
KEYWORDS office building, thermal performance, air movement

#NO 3462 Modelling heat, moisture and contaminant transport in buildings: toward a new generation software.
AUTHOR Kerestecioglu H, Swami M, Fairey P, Lixing G, Chandra S
BIBINF USA, Florida Solar Energy Center, FSEC-PF-165-89, 1989, 8pp, 9 figs, 11 refs. #DATE 00:00:1989 in English

ABSTRACT This paper describes a general purpose software, Florida Software for Engineering Calculations, that is capable of solving various transport equations used in building science (eg combined heat and moisture transfer, fluid flow, contaminant dispersion equations, etc). The governing equations are solved by finite element methods. General capabilities and an overview of the software structure are given. Results are presented for several types of combined heat and moisture transfer simulationsL 1) in buildings; 2) in the presence of natural convection; 3) in attics 4) in a typical wall.
KEYWORDS contaminant, computer, moisture, attic, wall

#NO 2161 Model tests of ventilation effectiveness and air distribution - literature survey.
AUTHOR Klobut K.
BIBINF Report C:13, Espoo, Finland:Helsinki University of Technology, Laboratory of Heating, Ventilation and Air-Conditioning, Indoor Climate Project, 1985. 114p, 34 figs, 8 tabs, 84 refs. #DATE 00:00:1985 in English .
ABSTRACT A survey of mathematical models of air flow and of ventilation efficiency. Measuring equipment for laboratory experiments is described and the limitations and potential uses of the models are discussed.
KEYWORDS mathematical modelling, air flow, ventilation efficiency

#NO 5306 Simultaneous calculation of airflows, temperatures and contaminant concentrations in multi-zone buildings.
AUTHOR Klobut K, Tuomaala P, Siren K, Seppanen O
BIBINF UK, AIVC 12th Conference, "Air Movement and Ventilation Control within Buildings", held 24-27 September 1991, Ottawa, Canada, proceedings published September 1991, Volume 3, pp 103-122. #DATE 00:09:1991 in English
ABSTRACT The computer programs published so far have enabled the calculation of airflows at constant temperatures or of air temperatures at constant airflows. The first version of a new microcomputer program has now been developed in which the airflows and temperatures are calculated simultaneously. The time-dependency of temperatures, airflows and contaminant concentrations is considered in the calculation method. The source strength of contaminants, outdoor air temperature, wind velocity and direction, convection and radiation loads can all be freely scheduled. The supply air temperature in mechanical ventilation can be selected as: (1) constant (and scheduled), (2) equal to that of the outdoor air, (3) calculated as the temperature of the mixture of outdoor air and return air. Constant-temperature cases were simulated with the program and the results compared with those obtained from more sophisticated programs. Other cases, with variable temperatures, were compared with the measurements. Good agreement of the results was obtained in all cases. The paper describes the main features of the new program and gives some simulation results.
KEYWORDS calculation techniques, air flow, temperature, contaminant, multizone building

#NO 4674 The numerical computation of turbulent flows.
AUTHOR Launder B E, Spalding D B
BIBINF Computer Methods in Applied Mechanics and Engineering, Vol 3, 1974, pp 269-289, 51 refs. #DATE 00:00:1974 in English
ABSTRACT The paper reviews the problem of making numerical predictions of turbulent flow. It advocates that computational economy, range of applicability and physical realism are best served at present by turbulence models in which the magnitudes of two turbulence quantities, the turbulence kinetic energy K and its dissipation rate E, are calculated from transport equations solved simultaneously with those governing the mean flow behaviour. The width of applicability of the model is demon-

strated by reference to numerical computations of nine substantially different kinds of turbulent flow.
KEYWORDS turbulence, calculation techniques

#NO 3291 Air Infiltration Calculation Techniques - An Applications Guide.
AUTHOR Liddament M W
BIBINF UK, AIVC Applications Guide 1, 1986 #DATE 00:00:1986
ABSTRACT A Loose leaf handbook divided into six chapters covering empirical and theoretical calculation techniques. algorithms, references and glossary of terms.
KEYWORDS calculation techniques

#NO 4928 Numerical database for the AIVC.
AUTHOR Liddament M W
BIBINF Air Infiltration Review, Vol 10, No 4, September 1989, pp 12-13, 2 figs. #DATE 00:09:1989 in English
ABSTRACT As part of its new operating programme, the Air Infiltration and Ventilation Centre is establishing a numerical database to be used both in support of design studies and for the verification of numerical models (Fig. 1) In addition to being available as a computer database, it is intended to present selected source data and simple algorithms in loose leaf form as a new volume in the AIVC's series of Application Guides.
KEYWORDS numerical modelling

#NO 5012 A review of building air flow simulation.
AUTHOR Liddament M W BIBINF UK, Air Infiltration and Ventilation Centre, Technical Note 33, March 1991, 40pp. #DATE 00:03:1991 in English
ABSTRACT The objective of this report is to outline recent developments in building air flow analysis and to focus on some of the difficulties associated with this complex field of study. Considerable developments in the area of computational fluid dynamics are currently taking place, especially in relation to refinements in calculation techniques. Rather than present an in-depth study of these developments, this report concentrates on the more general aspect of air flow in buildings. Bibliographic references are restricted to recent publications taken from the Air Infiltration and Ventilation Centre's Bibliographic Database - AIRBASE, which illustrate specific building examples and case studies. The appendices section contains references to related activities. These include a brief outline of the relevant flow equations, the results of the Centre's survey into the application of air flow codes for building air flow simulation, and summaries of selected public domain and commercial general purpose algorithms. An indication of the computer requirements for the use of these codes is also given.
KEYWORDS air flow, simulation

#NO 3549 Trends in airflow design and management, contributions by IEA Annex 20
AUTHOR Moser A

BIBINF in: UK, 10th AIVC Conference Proceedings Volume 1, held Espoo, Finland, 25-28 September 1989, published February 1990, pp45-62, 4 figs, 12 refs #DATE 00:02:1990 in English

ABSTRACT What does the designer of a future energy-efficient building ask of the air flow specialist? - Static predictions of air flow patterns and optimization of thermal comfort and indoor air quality at design conditions will not be enough for him. The paper suggests that time-dependent air flow simulation is imperative to respond to tomorrows design needs. Different physical time scales for air flow patterns in spaces will be discussed. Heat capacity by components, different types of heat transfer, varying occupancy, control inputs etc. give rise to disparate time scales. The trend toward occupant controlled ventilation will continue. Air Flow will interactively be adjusted to changing needs in each room. The IEA Annex 20 examines tools to predict steady air flow patterns within buildings. The dynamic management of air flows will require new methods that build on Annex 20 work.

KEYWORDS air flow, occupant control

#NO 5242 The message of Annex 20: air flow patterns within buildings.

AUTHOR Moser A

BIBINF UK, AIVC 12th Conference, "Air Movement and Ventilation Control within Buildings", held 24-27 September 1991, Ottawa, Canada, proceedings published September 1991, Volume 1, pp 1-26. #DATE 00:09:1991 in English

ABSTRACT This survey paper reviews project objectives and approach, both technically and from the point of view of project management. It offers an overview of the work performed and solutions contributed by the participating countries, it discusses problems encountered during the project and how these were solved, and summarizes final results. It shows how the various technical Annex-20 contributions to this conference are related to the overall Annex effort. General conclusions for future international projects are examined, and the main message of the multi-national program is formulated.

KEYWORDS air flow, simulation, single zone, multizone, measurement technique

#NO 4864 Reporting guidelines for the measurement of airflows and related factors in buildings.

AUTHOR Piggins J M, Harrje D T

BIBINF UK, AIVC 11th Conference, "Ventilation System Performance", held 18-21 September 1990, Belgirate, Italy, Proceedings published March 1990, Volume 2, pp 233-264, 13 figs, 2 tabs, 14 refs. #DATE 00:03:1991 in English

ABSTRACT A set of reporting guidelines has been established. The guidelines take into account the need for data concerning airflow within buildings and air exchange between a building and its surroundings. They also deal with issues such as pollutant production and transport, thermal properties and measurements of buildings and comfort related issues. The comprehensive nature of these guidelines should enable a large amount of data to be accrued in a form suitable for computer modelling and validation work. The extensive use of computers in research has thus been considered

and an application is under development to allow a research report to be entered directly into a relational database according to the framework of the guidelines. This will allow a research report to be directly accessible in the AIVC numerical database along side the data it refers to.
KEYWORDS air flow, air change rate, pollutant

#NO 5358 Building simulations using thermal and CFD models.
AUTHOR Setrakian A, McLean D
BIBINF France, Building Simulation '91 Conference, held 20-22 August 1991, Sophia-Antipolis, Nice, France, published by IBSPA (The International Building Performance Simulation Association), 1991, pp 235-242. #DATE 00:00:1991 in English
ABSTRACT This paper describes two simulation software packages which permit building designers to understand how buildings will perform: the ESP building energy simulation system and the ARIA Computational Fluid Dynamics (CFD) air distribution simulation system. One of the major problems with CFD code is the specification of boundary conditions for the problem. ESP can provide the boundary conditions information for the CFD airflow simulation. Two brief case studies are presented which illustrate the ability to provide the boundary conditions for the CFD problem from ESP.
KEYWORDS simulation, numerical modelling, thermal analysis

#NO 5707 Applications of computational fluid dynamics in building services engineering.
AUTHOR Setrakian A A, McLean D J, Morgan D A
BIBINF UK, London, Institution of Mechanical Engineers, paper from a conference "Computational fluid dynamics - tool or toy?" held 26 November 1991, pp 33-37, 6 figs, 7 refs. #DATE 26:11:1991 in English
ABSTRACT This paper describes the advantages of using a customised Computational Fluid Dynamics (CFD) software program designed for use in building services engineering. The minimum requirements of a building services CFD program are detailed. Case studies are also presented as example results of having such a code.
KEYWORDS computational fluid dynamics, computer, modelling

#NO 5631 A new development in air conditioning.
AUTHOR Stahl M, Keller G M
BIBINF USA, Ashrae, Transactions, Vol 98, Part 1, 1992, 9pp, 15 figs, refs. #DATE 00:00:1992 in English
ABSTRACT Ventilation by heat sources and a cold ceiling-these two terms and the technology behind them have been the main topics discussed in the European ventilation and air-conditioning trade for about two years. The characteristics of this new air-conditioning system, which many experts call the "system of the future," have been presented at many recent international specialist meetings and congresses. Most of the papers focused on the advantages, such as "increased comfort," "savings in energy and space," "avoidance of draft due to low air velocities," and "decoupling the removal of the thermal load from the necessary volume of supply air." In Scandinavia and the

West European countries in particular, the technology has spread. Even if many planners and architects still are skeptical about the system of ventilation by heat sources and a cold ceiling, the technology's international advancement seems to be only a matter of time. This paper, however, will not go into the scientific fundamentals of the system. It will present the mode of operation of a cold ceiling combined with a system of heat-source ventilation and then give a survey of the state of the technology. Some examples of application, which not only show the manifold possibilities but also the limits and disadvantages of this system, will be presented.
KEYWORDS ventilation system, ceiling, air conditioning

Pressure Coefficients on Sheltered Buildings
Walker I.S, Air Infiltration Review, Sept 1992, volume 13, No 4.

#NO 1364 Airflow and multi-room thermal analysis.
AUTHOR Walton G.N.
BIBINF ASHRAE Trans.Tech.Paper No.2704 vol.88 part 2 1982 11pp. 7 figs. 14 refs.
#DATE 01:01:1982 in English
ABSTRACT Presents a model for computing the infiltration and air flow between rooms of a multi-room building in terms of basic principles of fluid mechanics. This model has been incorporated into a comprehensive loads-predicting computer program. Air flows, room temperatures, and heating loads for a typical townhouse under different conditions of environment and with various construction features are computed. These calculations show the feasibility of detailed multi-room air movement analysis. They also indicate that when the inter-room openings of low-rise structure are large compared to the envelope openings, the infiltration and total load can be accurately and more quickly computed by assuming no resistance to air flow between rooms. This property will also allow simplified calculations for high rise buildings with many rooms. Methods are proposed for handling more complex air flow phenomena.
KEYWORDS air flow, modelling, multi_chamber,

#NO 1563 A computer algorithm for predicting infiltration and interroom airflows
AUTHOR Walton G N.
BIBINF ASHRAE Trans, 1984, Vol 90, Part 1B, p601-610, 5 fig, 12 ref. #DATE 00:00:1984 in English
ABSTRACT This report discusses the extension of an infiltration predicting technique to the prediction of interroom air movements. The airflow through openings is computed from the ASHRAE crack method together with a mass balance in each room. Simultaneous solution of the mass balances in all rooms having both large and small openings is accomplished by a slightly modified Newton method. A simple theory for two-way flow through large openings is developed from consideration of density differences caused by different temperatures in adjoining rooms. The technique is verified by comparison to published experimental results. The results indicate that the simple model provides reasonable results for complex two-way flows through openings. The model is as accurate as the available data, that is, about plus or minus 20%. The

airflow algorithm allows infiltration and forced airflows to interact with the doorway flows to provide a more general simulation capability.
KEYWORDS mathematical modelling, prediction, simulation, air infiltration, air movement

#NO 3464 AIRNET - a computer program for building airflow network modeling.
AUTHOR Walton G N
BIBINF USA, Gaithersburg MD, Dept of Commerce, National Institute of Standards and Technology, NISTIR 89-4072, April 1989, 77pp, 11 figs. #DATE 00:00:1989 in English
ABSTRACT In spite of its importance, the analysis of airflows has significantly lagged the modeling of other building features because of limited data, computational difficulties, and incompatible methods for analyzing different flows. Methods have been developed to analyze airflows in HVAC ducts and to estimate infiltration but the interaction between building HVAC ducts systems and infiltration airflows has seldom been studied. This report describes a computer program for modeling networks of airflow elements, such as openings, ducts, and fans. It emphasizes the numerical aspects of an airflow network method which would provide a unified approach to building airflow calculations. It also discusses the limitations of the method and poorly understood factors that could profit from further research.
KEYWORDS computer, air flow, modelling, duct, fan, ventilation system

#NO 5243 Evaluation of measured and computer test case results from Annex 20, Subtask 1.
AUTHOR Whittle G
BIBINF UK, AIVC 12th Conference, "Air Movement and Ventilation Control within Buildings", held 24-27 September 1991, Ottawa, Canada, proceedings published September 1991, Volume 1, pp 27-54. #DATE 00:09:1991 in English
ABSTRACT IEA Annex 20 is a task-sharing project on "Air flow patterns within buildings". The objective is to evaluate the performance of single- and multi-zone air and contaminant flow simulation techniques and to establish their viability as design tools. In subtask 1 of the Annex, which deals with single-zone spaces, laboratory experiments in similar test rooms and computer simulations have been carried out at a number of sites in Europe and North America. The data comprises information on air flow patterns and on point-by-point values of mean velocity, turbulent velocity, temperature and contaminant concentration throughout a space. This paper outlines an initial evaluation of this data and highlights some of the features which the comparisons of measured and computed room air distribution have yielded. Work is continuing in completing the evaluation for tests and data not reported or discussed here.
KEYWORDS air movement, air distribution, thermal comfort, ventilation effectiveness

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