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Implementation and evaluation of air flow and heat transfer routines for building simulation tools

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VTT Building and Transport

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To my dearest ones: Eija, Emilia and Mikael

Some men see things as they are, and say "Why ?" —
I dream things that never were, and say "Why not ?"

- JFK -

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Abstract

Environmental, epidemiological and economical reasons increase the pressure to design, construct and maintain better buildings in the future. Therefore, a new assembly of simulation routines for predicting both ventilation and heat transfer processes of buildings were studied. The work was limited to implementation and evaluation of new air flow and heat transfer routines for building simulation tools. Development of simulation tool user-interfaces, post-processors and component database have all been excluded.

The simulation routines were implemented in a new building simulation tool BUS++, which was based on discretisation and solution of mass, momentum, and heat balance equations. Ventilation fans, external wind and thermal buoyancy were included as driving forces for air infiltration and ventilation process. Two completely new routines were developed and implemented to obtain more reliable estimations of dynamic and multi-mode heat transfer covering thermal convection, conduction, and radiation. The first new routine focused on defining a rational thermal calculation network, and the second one concentrated on simulation of thermal radiation in a room. Finally, a rigorous set of tests were conducted to validate the air flow and heat transfer routines implemented in BUS++. The test set included commonly utilised analytical verifications and inter-model comparisons as well as completely new empirical validation test cases.

The new rational gridding method reduced simulation times by 44 % to 86 % in a typical slab test case with a cyclic excitation, and the new routine for thermal radiation was up to ten times faster than the conventional matrix radiosity method. In addition, the simulation and validation data showed good agreement, especially for the analytical verifications and inter-model comparisons with typical differences less than 2 %. Despite these promising results, more research

work is needed to further develop the simulation routines. In the future, special attention ought to be paid to simulation tool user-interfaces to facilitate full utilisation of the simulation tool by a wide range of users.

Preface

This study was carried out at Helsinki University of Technology (HUT) and Technical Research Centre of Finland (VTT). The original motivation for this work came from the practical need for a better and more thorough understanding of thermal and ventilation performance of buildings, and the aim of this study was to implement and evaluate air flow and heat transfer routines for building simulation tools.

Chapter 1 of this thesis provides a brief introduction to the topic of this study and includes a review of some existing, and maybe most commonly utilised simulation tools. Chapter 2 presents common methods of simulating thermal and air flow process in buildings, and the methods adopted and developed in this study. In Chapter 3, the developed building simulation routines are validated with analytical, simulated and measured data. Chapters 4 and 5 include discussions and conclusions related to this study, respectively.

First of all I want to express my gratitude to all co-authors of the scientific articles: Dr. Jussi Rahola, Prof. Carey Simonson, Kalevi Piira and Mika Vuolle. In addition, special thanks are due to Prof. Timo Siikonen, for providing me with fundamental ideas and theoretical tools to develop the air flow simulation model, and especially to Prof. Ilmari Kurki-Suonio, Prof. Markku Lampinen, and Prof. Carey Simonson for the fruitful discussions and support that I have received while writing this thesis.

Espoo, Finland

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Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://otatrip.hut.fi/vtt/jure/index.html)

List of original publications

This thesis is based on the following papers referred to in the text by the Roman numerals I–V:

I Tuomaala, P. 1993. New Building Air Flow Simulation Model: Theoretical Basis. Building Services Engineering Research and Technology, Vol. 14, Number 4, pp. 151–157.

II Tuomaala, P. and Rahola, J. 1995. Combined Air Flow and Thermal Simulation of Buildings. Building and Environment, Vol. 30, Number 2, pp. 255–265.

III Tuomaala, P., Piira, K. and Vuolle, M. 2000. A Rational Method for the Distribution of Nodes in Modelling of Transient Heat Conduction in Plane Slabs. Building and Environment, Vol. 35, pp. 397–406.

IV Tuomaala, P. and Piira, K. 2000. Thermal radiation in a Room: An Improved Progressive Refinement Method. Building Services Engineering Research and Technology, Vol. 21, Number 1, pp. 9–17.

V Tuomaala, P., Simonson, C. J. and Piira, K. 2002. Validation of Coupled Airflow and Heat Transfer Routines in a Building Simulation Tool. Accepted for publication in ASHRAE Transactions, Vol. 108, Number 1, pp. 435–449.

List of symbols

NOMENCLATURE

Acronym	***Definition***
BUS++	a new building simulation tool developed for this thesis
CFD	Computational Fluid Dynamics
DAE	Differential-Algebraic Equations
DOD	U.S. Department of Defence
DOE	U.S. Department of Energy
IPRM	Improved Progressive Refinement Method
NMF	Neutral Model Format
MSE	Modular Simulation Environment
OOP	Object-Oriented Programming

Symbol	***Units***	***Definition***
a_{ij}	-	value of a matrix component
A_i	m^2	surface area of node *i*
A_{ij}	m^2	cross sectional area of the flow element between nodes *i* and *j*
b_i	-	value of vector component *i*
Bi_s	-	surface Biot number
C_i	$\mathrm{J\ K}^{-1}$	heat capacity of node *i*
E_i	$\mathrm{W\ m}^{-2}$	radiative heat emission
$F_{i\text{-}j}$	-	view factor between nodes *i* and *j*
G_i	$\mathrm{W\ m}^{-2}$	irradiance
G_{ij}	$\mathrm{W\ K}^{-1}$	conductance between nodes *i* and *j*
h	$\mathrm{W\ m}^{-2}\ \mathrm{K}^{-1}$	convective heat transfer coefficient
h_{ij}	$\mathrm{J\ kg}^{-1}$	enthalpy of the flow element between nodes *i* and *j*

J_i	W m^{-2}	radiosity
K_{ij}	Pa kg^{-2} s^2	pressure loss coefficient of the flow element between nodes i and j
L_{ij}	m	length of the flow element between nodes i and j
$\dot{m}_{ij}$	kg s^{-1}	mass flow rate between nodes i and j
p_i	Pa	pressure at node i
Δp_i	Pa	pressure correction at node i during an iteration loop
q	-	space increment ratio
q_i	W	net surface radiation flow
S_i	kg s^{-1}	mass source at node i
S_{ij}	Pa	pressure source in the flow element between nodes i and j
t	s	time
Δt	s	time step
T_i	K	temperature of node i
V	m^3	volume
Δx	m	space increment

Greek letters

λ	W m^{-1} K^{-1}	thermal conductivity
ρ	kg m^{-3}	density
ρ	-	reflectivity
Φ_i	W	heat load in node i

Superscript

$p+1, p$	iteration indices
$t-\Delta t$	values during previous simulation time step

1. Introduction

The total energy consumption in Finland was about 350 TWh in 1996, and a quarter of this was consumed by the Finish building stock for space heating and ventilation (Statistics Finland 1996). Obviously, the amount of energy required to heat, cool and ventilate buildings depends on both the local climate and national customs. Nevertheless, the building sector plays a significant role in global energy consumption, and accurate assessment of building energy consumption is important because buildings in developed countries typically account for 30 % to 50 % of national energy consumption (Liddament and Orme 1998). Since energy production is extensively based on utilising fossil fuels in most countries, the building sector has a clear connection to environmental issues.

People in Finland and other developed countries spend approximately 90 % of their time indoors and most of the time in dwellings (Dorre et al. 1990). The cost of poor indoor air quality (including sick leaves, health care costs and lost productivity) in the Finnish building stock has been estimated to be equal to the cost of energy consumption of ventilation which is over 2 300 million € per year (Seppänen 1999). Studies in other countries have shown similar results demonstrating that indoor air quality is a very important issue.

Environmental, epidemiological and economical reasons increase the pressure to design, construct and maintain better buildings in the future. Therefore, more research is needed to better understand the behaviour of buildings, and particularly to quantify the interaction between indoor air quality, comfort, ventilation and energy consumption. (Wargocki et al. 2000 and Seppänen et al. 1999)

There are two main strategies to understand and predict the behaviour of buildings: experimental investigation and theoretical calculations. Although experimental investigations represent the performance of buildings in practice, they are often extremely expensive because of investment and running costs are high and complex instrumentation is needed. In addition, the results of field measurements are often difficult to interpret because of the large number of variables, and repeatable experiments are often difficult to perform (Sahlin 1996).

Theoretical calculations, on the other hand, only model reality and require extensive validation to ascertain their uncertainty. Once theoretical and numerical models have been evaluated, they have several advantages compared to experimental investigations. Calculations are relatively quick, easy and inexpensive to perform. Furthermore, the simulation results can be obtained independently of external factors (e.g., outdoor air temperature variations) and any combination of these factors can be selected and given freely as input parameters to a simulation tool. Sometimes a very important issue is that the theoretical calculations can also be performed independently of time (e.g., the annual energy consumption of a building can be calculated in a much shorter period of time than measurements would require). One of the greatest advantages of theoretical calculations is, however, the complete information of the simulated process. This means that all of the calculated values of the variables are available for further investigation. This is an important advantage compared, for example, to experimental investigations where the appropriate placement of a limited number of measuring devices must be decided a priori. Even if the important locations can be identified, information about the process will be lacking because of its complexity and the disturbance caused by the measuring devices. Another significant advantage of theoretical calculations is their ability to investigate the sensitivity of individual parameters, which allows designers to efficiently compare different designs.

Building simulation is an interdisciplinary subject, with elements from numerical analysis, information technology, signal processing, as well as the building sciences (Sahlin 1996). This makes it a fascinating field with the endless challenge to estimate interacting energy flow paths encountered within buildings with a meaningful level of accuracy. Further complexity comes from the behaviour of the heat and mass transfer mechanisms themselves, because they are often highly non-linear, coupled and are dependent on design parameters which, in turn, change with time (Clarke and Maver 1991).

A completed building simulation tool has three main classes of potential users, each group having different requirements:

– building designers,
– government policy makers, and
– research scientists.

These users can apply a simulation tool to pre-construction testing, indoor air quality prediction, energy efficient heating and ventilation design, and design validation (Kendrick 1993).

1.1 A literature review

More than 50 infiltration and ventilation models have already been developed during the last few decades (Liddament and Allen 1983, Haghighat 1989, Feustel and Dieris 1992). Most of these programs calculate only the air flow rates, but some comprehensive integrated simulation models (in which also the thermal analysis of a building is included) have also been developed. In addition, most of the simulation programs of both groups still lack the ability to simulate both steady state and transient problems. (Kendrick 1993)

The US Department of Energy (DOE) has compiled an extensive summary of building simulation tools (www.eren.doe.gov/buildings/tools_directory/), which describes more than 200 energy-related software tools for buildings, with an emphasis on using renewable energy and achieving energy efficiency and sustainability in buildings. In the following paragraphs, a brief description of five of the most commonly used building simulation tools is provided to show typical features of tools.

DOE-2 is a tool that uses hourly weather data to simulate a building's energy use and energy cost for a given description of the building's indoor climate, architecture, materials, operating schedules, and HVAC equipment. The development has been funded by the U.S. Department of Energy. It is used for building science research, teaching, designing energy-efficient buildings, analysing the impact of new technologies and developing energy conservation standards. Example applications that have been studied include advanced insulating materials, evaporative cooling, daylighting, desiccant cooling, cogeneration, gas-engine-driven cooling, cold storage, effect of increased ventilation, sizing of thermal energy storage systems, gas heat pumps, thermal bridges, thermal mass, and window performance labelling. In addition, there are available commercial front-end software compatible with the original DOE-2, including graphical user-interfaces, on-line-help, documentation and libraries for materials, structures, windows, building prototypes, weather files, and schedules. (http://www.eren.doe.gov/buildings/tools_directory/)

EnergyPlus is a building simulation program that is currently being developed by the Simulation Research Group at Lawrence Berkeley National Laboratory, the Building Systems Laboratory at the University of Illinois, the U.S. Army Construction Engineering Research Laboratory, and U.S Department of Energy. Development of EnergyPlus is based on experience with two existing programs: DOE-2, sponsored by U.S. Department of Energy, and BLAST, supported by U.S. Department of Defence (Pedersen et al. 1997 and Crawley et al. 2000). In general, the development work is aiming to combine the best capabilities and features from BLAST and DOE2 along with new capabilities. (http://www.eren.doe.gov/buildings/tools_directory/)

ESP-r is a comprehensive simulation environment which can assess problems related to several domains. It has been developed at the Strathclyde University in Scotland since 1974. ESP-r allows researchers and designers to assess the manner in which actual weather patterns, occupant interactions, design parameter changes and control systems affect energy requirements and environmental states. It is used in many European universities and research institutes, and in some private companies. Within ESP-r, it is possible to select different approaches to domain solution – one, two or three dimensional calculation, a mix of scheduled air flow, network or computational fluid dynamics (CFD) for flow assessments, and a mix of ideal or explicit representations of plant and control systems. (www.esru.strath.ac.uk/esru.html)

IDA is an advanced simulation environment for building and energy system simulation. It has originally been developed at the Swedish Institute of Applied Mathematics in co-operation with the department of Building Services Engineering at Royal University of Stockholm. This simulation package consists of IDA Modeller, IDA Solver, and an Neutral Model Format (NMF) library. The key is to separate models, which are defined by free combinations of algebraic and differential equations in NMF format, and the solver. By adopting this approach, several practical problems with traditional monolithic simulation tools can be avoided (Sahlin 1996). Namely, new building component models can be described in NMF format, and they still can be solved by a differential-algebraic equation (DAE) solver without any need to rewrite simulation and solution source code. (www.equa.se)

TRNSYS was developed during the early seventies at the Solar Energy Laboratory at the University of Wisconsin. The primary application was initially solar energy systems. Several compatible modelling tools have been developed independently, e.g., PRESIM and IISiBat. An important feature of TRNSYS is that component models are pre-compiled. This means that end users may compose system models with fixed components without access to a compiler (Sahlin 1996). Historically, TRNSYS has been used for simulating solar thermal systems, modern renewable energy systems including PV and wind power, more general HVAC systems, and buildings. TRNSYS 14.2 features many improvements to the existing graphical user-interface programs in the TRNSYS package and the addition of an alternative front-end for TRNSYS and IISiBat. (http://sel.me.wisc.edu/trnsys/)

Each simulation tool has special features and some limitations. For example, DOE-2 is based on a simplified modeling approach which makes it difficult to include new systems and devices in the model. This has lead to a whole new development effort (i.e., EnergyPlus), which is still going on (Crawley et al. 2000). ESP-r is a very comprehensive simulation environment, but this simulation tool is available only in special mainframe computers using the Unix operating system (Hand 1988). IDA is a modern and promising simulation environment. It is becoming gradually more popular, but some problems with long execution times has been reported. The latest version of TRNSYS features many improvements, and it has been utilised successfully in many cases. However, TRNSYS also has some limitations due to adopted fundamental modelling methods. Therefore, despite the fact that a great effort has been put in developing all the existing building simulation tools, additional work is needed to rectify their deficiencies.

1.2 Aim of this study

The aim of this study is to implement and evaluate robust and powerful air flow and heat transfer routines for building simulation tools. The work is limited to the development and validation of simulation routines, focusing on a time-dependent simulation of air infiltration and ventilation processes, and multi-mode heat transfer of buildings – as well as interactions between these processes. A key aim is to develop routines that provide rapid convergence to an accurate solution. Development of simulation tool user-interfaces, post-processors and component data base have all been excluded.

2. Building simulation tool

This chapter gives general information about building simulation tools. Two classification alternatives for simulation tools are presented, and different air flow simulation approaches and thermal simulation methods are listed and briefly discussed. In addition, this Chapter presents the simulation routines developed and adopted in this thesis.

2.1 Classifications of building simulation tools

There are several alternatives to classify building simulation tools. Clarke and Maver (1991) suggest classification of building simulation tools by four generations:

1st generation: Such tools are handbook oriented computer implementations, analytical in formulation, and biased towards simplicity. They often lack rigorous approach, and thus provide only indicative results within constrained solution domains.

2nd generation: Such tools are characterised by the introduction of the dynamics of fabric response, but are decoupled in relation to the treatment of air movement, systems and control. Early tools were decoupled from the design process by limited interfaces and computational requirements which were substantial for their time. Later implementations are often marketed on their ease of use and speed of solution.

3rd generation: Such tools are characterised by treating the entire building as a coupled field problem and employing a mix of numerical and analytical techniques. These tools demand considerable experience and resources to go beyond simple problems. Interfaces are able to reduce some barriers to their use. Modelling integrity is enhanced but the tools are often used to derive information to be incorporated in simplified techniques.

4th generation: Such tools are characterised by full computer-aided building design integration and advanced numerical methods which allow integrated performance assessments across analysis domains. Interfaces and underlying data models are evolved to present and operate on simulation entities as objects in the user's domain. One common evolution is the incorporation of knowledge bases within the tool infrastructure.

It is recommended by Hand (1998) that the first and second generations be referred to as *simplified methods* because of their constrained treatment of the underlying physics, and the third and fourth generations be referred to as *simulation*. Tools which focus on a specific assessment domain (e.g., computational fluid dynamics, thermal bridges, glazing system design) may fall into either category, depending on their treatment of the underlying physics (Hand 1998).

Sahlin (1996) suggests classification by *modular* vs. *traditional* tools. Many different interpretations of the term *modular method* exist, and others, such as *object oriented* or *modular simulation environment* are often used with nearly the same meaning which leads to misunderstandings in the scientific debate. According to Sahlin's definition, modular simulation environments (MSE) are completely independent from object oriented programming (OOP). MSEs may or may not be implemented with OOP tools, but recent developments generally are. Sahlin presents two criteria that an MSE must fulfil, which are:

1. Models are treated as data. The key characteristic of an MSE is that the mathematical models are exchangeable. The environment allows radically different models to be used for the same physical device.

2. Software modules for modelling and solution are separated. The software architecture allows exchange of solvers. Although only a few MSEs really offer a selection of different solvers, they are flexible in this respect.

If characterised by equations, the physical systems under consideration will require both algebraic and differential equations, and MSEs allow a free mixture of algebraic and ordinary differential equations generally referred to as differential-algebraic systems of equations (DAE) (Sahlin 1996).

There are other classifications available as well, but the two alternatives presented above are the most generic ones. Other classifications are usually based on the level of detail within specific areas of interest (i.e. air infiltration and ventilation, heat transfer, indoor air quality, etc), as presented later in this chapter.

2.2 Air flow simulation approaches

The prediction of air infiltration and ventilation rates in buildings is required for indoor air quality and energy conservation applications. In practice, the choice of calculation technique varies according to the required level of accuracy, the availability of data and the type of building under investigation. Consequently, a wide variety of methods have been developed to cope with the problems of estimating the rates of air infiltration in buildings, with no single method being universally appropriate. Despite the many methods, prediction techniques have been grouped into five generic forms by Liddament (1986):

a. 'air change' methods,
b. 'reduction' of pressurisation test data,
c. regression methods,
d. theoretical flow network models, and
e. 'simplified' theoretical techniques.

Methods a–c are essentially empirical techniques in which the calculation of air infiltration is loosely based on the theoretical principles of air flow. While these methods tend to be fairly straightforward to apply, they usually have a rather limited range of applicability. The remaining methods are based on a much more fundamental approach and solve the equations governing air flow through openings in the building envelope. These methods have a potentially unrestricted range of applicability but can be very demanding in terms of computer execution time and data requirements (Liddament 1986).

Feustel and Dieris (1992) suggest classification of air infiltration and ventilation tools by considering whether one wants to predict detailed air flow and contaminant distribution patterns in rooms (*Room air movement models*) or in buildings (*Building air movement or network models*). Room air movement models are focus on predicting the local two- or three-dimensional air flow and contaminant distribution patterns in a room by various CFD algorithms (Schulte et al. 1998), while building air movement models focus on the mean air flow distribution in a building. Building air movement models use a network approach, where nodes representing zones of differing pressure, temperature and contaminant concentration are interconnected by flow elements. In most models, uniform and instant mixing is assumed for each zone. Although the level of analysis is not nearly as detailed as a room air movement model, a network approach is better suited for simulation of entire buildings because it can provide an overall picture of air flow and contaminant concentration patterns in the modelled building. Such a network model is applied in the model developed in this thesis.

2.3 Thermal simulation methods

There are several classification systems for building heat transfer simulation methods as well. Källblad (1983) has grouped building heat transfer simulation methods into more detailed *time-dependent methods* and *simplified methods*. The simplified methods can further be categorised as *steady-state heat balance*, *degree-day*, and *other methods* (Fig. 1).

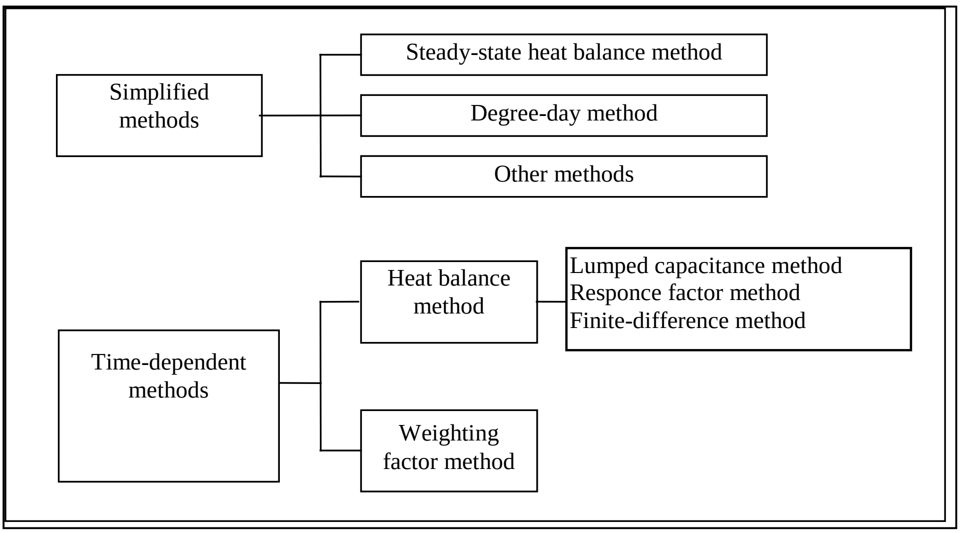

Figure 1. Heat transfer simulation methods (Källblad 1983).

Dynamic thermal simulation methods can be classified as *heat balance* and *weighting factor methods*, with the *heat balance method* giving more detailed output data than the weighting factor method. Most of the modern thermal models are based on the heat balance method (e.g., BLAST, SERIRES, HTB2, ESP, TASE), which is the method used in this study, but there are also models based on the weighting factor method (e.g. DOE 2.1, Kalema 1992).

When the heat balance method is used, the solution of the time-dependent temperature distribution within a solid during transient processes is often difficult to obtain. Therefore, where possible, a simple approach is preferred. One such approach is termed the *lumped capacitance method*, where the temperature of the solid is assumed *spatially uniform* at any instant during the transient process. This assumption implies that the temperature gradient within the solid is negligible. (Incropera and DeWitt 1990)

The *finite-difference method* is well suited and commonly utilised with digital computers and is applied here. In contrast to an analytical solution, which allows for temperature determination at *any* point in a medium, a numerical solution enables determination of temperature at *discrete* points only (Incropera and DeWitt 1990). Such a discrete point is frequently termed a *nodal point* (or simply a *node*), and the aggregate of points is termed a *nodal network*, *grid* or *mesh*. It is important to note that each node represents a certain region, and its temperature is a measure of the *average* temperature of the region.

2.4 Methods of the present study

In this chapter, the basic governing equations, assumptions and solution methods used in BUS++ are presented. The simulation of air flow and heat transfer is based on a network assumption. Ventilation fans, external wind and thermal buoyancy effect are included in the program as driving forces of the infiltration and ventilation process (Papers I and II). A multi-mode heat balance method – with the presence of thermal conduction, convection, and radiation – is adopted. Coupled air flow and heat transfer is solved by iterating the mass, momentum, and energy balance equations until they are satisfied within a desired accuracy level.

2.4.1 Air flow simulation (Paper I)

Air flows in a building are caused by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems or a combination of these (Fig. 2). Air flow is also influenced by the distribution of openings in the building shell, openings between rooms and actions of the occupants. Every air flow simulation model that uses the network approach must model these phenomena. Both the driving forces and flow elements need to be mathematically formulated and the resulting set of equations (describing the process to be simulated) must be solved, so that the conservation laws (mass, momentum, energy) will be satisfied simultaneously. Because the flow rate is non-linearly dependent on the pressure difference, the flow distribution for a building can be calculated only by using an iterative method. (Feustel and Dieris 1992)

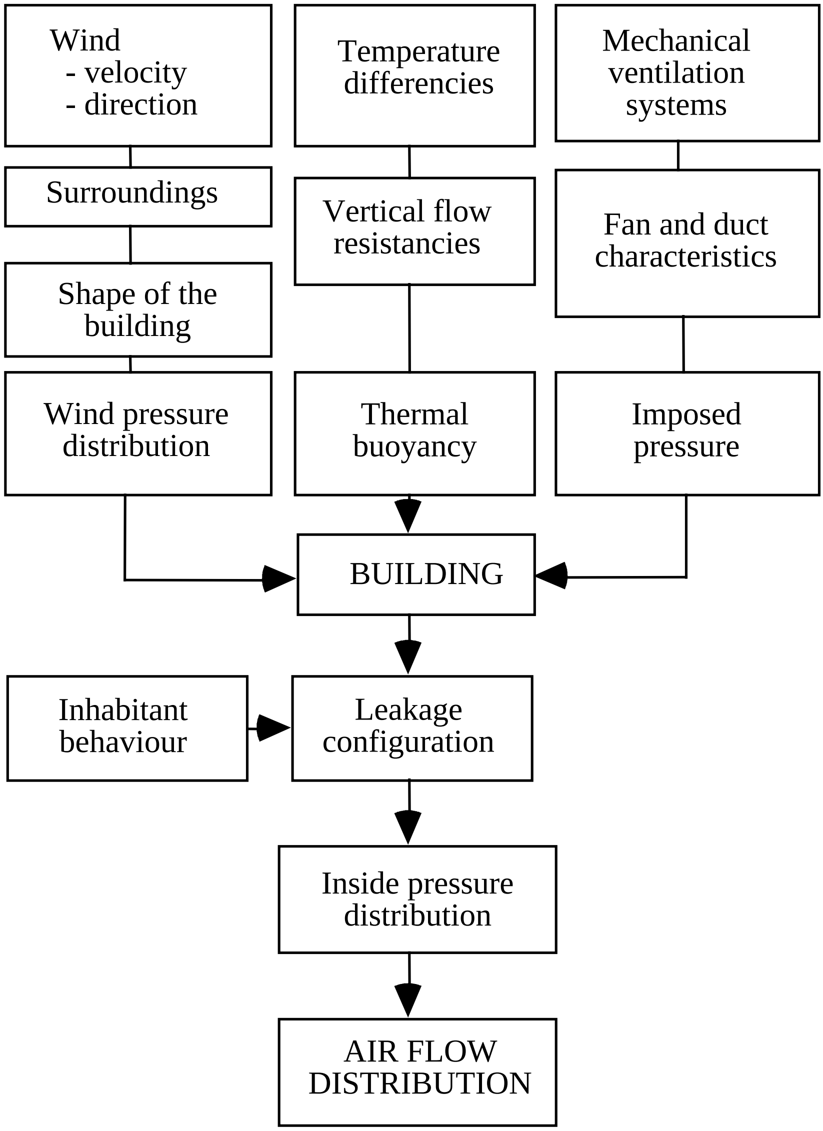

Figure 2. Factors that influence the air flow distribution in buildings (Feustel and Dieris 1992).

In BUS++, network nodes are connected to each other by one-dimensional flow elements. An effective and robust algorithm (Patankar 1980, Juslin and Siikonen 1983) is selected to solve the mass balance equations of every node, and the momentum equation for each flow element. These equations are linearised and solved iteratively using a fully implicit method. For individual air nodes in the network, complete and instant mixing of air is assumed. As mentioned above, ventilation fans, external wind and thermal buoyancy are modelled as driving forces. The behaviour of ventilation fans (under different flow conditions) are approximated in the model by using their flow characteristics as input data. When evaluating external wind pressure, the effect of building shape and surroundings are estimated by wind pressure coefficients. These coefficients are needed to be given for every infiltration and exfiltration flow element (i.e., opening) as input data. The effect of thermal buoyancy is approximated within single air flow elements by pressure differences caused by differences in connecting node heights and air densities.

The adopted algorithm is based on a simultaneous iterative solution of both the mass balance equation of each node in the network, and the momentum equation for each flow element (Fig. 3). A more detailed study of these governing equations is presented in Paper I, where the mass balance equation for every node is

$$V_i \frac{d\rho_i}{dt} + \sum_i \dot{m}_{ij} = S_i \,, \tag{1}$$

and, if the mass flow is assumed to be one-dimensional, the momentum equation can be expressed as

$$\frac{L_{ij}}{A_{ij}} \frac{d\dot{m}_{ij}}{dt} - p_i + p_j + \frac{1}{2} K_{ij} \left|\dot{m}_{ij}\right| \dot{m}_{ij} = S_{ij} \ . \tag{2}$$

Equation (2) shows that the relationship between the pressure difference across a single flow element and mass flow rate through the element is non-linear (except for ideal laminar flow). Because of this non-linearity of the momentum equation, an iterative solution method is needed. The new node pressures (superscript p+1) are calculated from the values of the previous iteration loop (superscript p) and the pressure corrections with the following equation:

$$p_i^{(p+1)} = p_i^{(p)} + \Delta p_i \ . \tag{3}$$

The pressure corrections, in turn, can be expressed as a linear system of equations (Paper I):

$$a_{ii}\Delta p_i = \sum_j a_{ij}\Delta p_i - b_i\,, \tag{4}$$

where coefficients a_{ij} and b_i depend on process flow conditions.

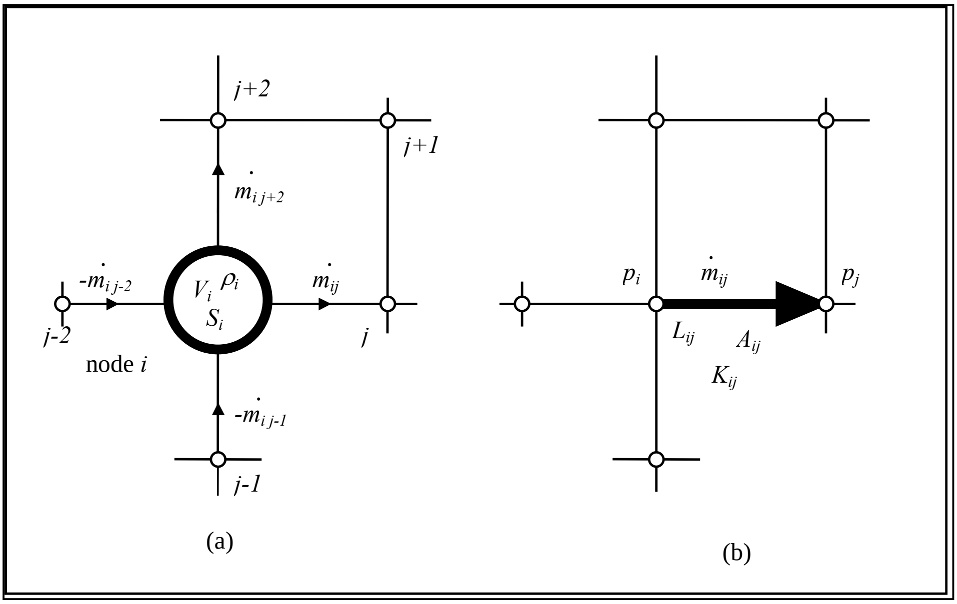

Figure 3. Parameters related to network nodes (a) and flow elements (b).

Once the pressure corrections are known at the end of an iteration loop, the mass flow rates are calculated based on the new node pressure values, and all pressure loss coefficients of the flow elements are updated as well. This iteration of pressure corrections and mass flow rates for each time step is continued until the residuals of the mass balance equations and momentum equations are smaller than the convergence criteria. When the convergence criteria are fulfilled, the pressures and mass flow rates for the next time step can be solved.

The assumptions made here are that the flow area and the velocity along a single flow element are constant, which means that inlet and outlet velocities are equal. Also the air density through a single flow element is assumed to be constant.

2.4.2 Thermal simulation (Paper II)

Heat transfer simulation – like air flow simulation – is based on the network approach. Adjacent nodes with thermal capacitances are connected with thermal conductances. Node temperatures are calculated by solving the heat balance equations of the nodes. The number of these nodes must, on one hand, be large enough to achieve a sufficient level of accuracy; but on the other hand, be small enough to avoid excessive computational effort (Hensen and Nakhi 1994). This has led to the development of a rational method for selecting nodes and grid sizes in heat transfer problems (Paper III), which is described in section 2.4.4.

A network heat balance method has been selected for the assessment of temperature levels and energy consumption of a building (Paper II). An implicit time discretisation is chosen to keep the solution stable with all time step values. A general energy balance equation for a single node, where also the mass transfer between nodes is included, is written as

$$C_i \frac{T_i - T_i^{t-\Delta t}}{\Delta t} + \sum_j G_{ij}\left(T_i - T_j\right) + \sum_j \dot{m}_{ij} h_{ij} = \Phi_i \ . \tag{5}$$

The heat source term on the right-hand side of Eq. (5) includes all heat power components of node *i* (e.g., electrical heating power inside a floor node, internal heat gains of a room air node, or net thermal radiation on a surface node).

Adopting a network heat balance method means that the temperature gradient within an individual thermal node is neglected. Each node represents a certain region, and its temperature is a measure of the *average* temperature of the region described by a single node. The second assumption is that all thermal properties and parameters are assumed to be constant during a calculation time step. However, the thermal parameter values can be updated between two time steps.

2.4.3 Sparse matrix solver (Paper II)

The preconditioned conjugate gradient (PCG) sparse matrix solver has been adopted and implemented in BUS++. The normal conjugate gradient method (CG) works for symmetric positive definite matrices. The matrices in this case are such matrices because they are symmetric and diagonally dominant, i.e. their diagonal elements are greater in absolute value than the sum of other elements in the same row. The conjugate gradient method produces iterates that are optimal in the sense that they minimise the second norm of the residual, $\| A\, \mathbf{x_k} - \mathbf{b} \|$. To reduce the number of iterations in iterative methods, the matrices are preconditioned, which means that the original linear system is multiplied by matrices that change the system into a more rapidly converging one. The preconditioned conjugate algorithm is described in Paper II.

2.4.4 A rational uneven thermal gridding of building structures (Paper III)

Only few guidelines and recommendations are available in the literature on the generation of a thermal network in practice, despite the fact that both time and spatial increments of a discretised heat transfer equation have a major influence on the accuracy of the numerical solution (Clarke 1985, Hensen and Nakhi 1994). Network generation is especially important because there are a wide range of building simulation problems with different desired levels of accuracy. In order to improve the understanding and application of network generation, a new method for defining the distribution of thermal nodes for transient thermal simulation of plane slabs is developed (Paper III). This rational gridding method describes a material as a thermal network with node capacitances and inter-nodal conductances allowing uneven gridding. Uneven gridding is a key element when making a rational trade-off between accuracy level and computation efforts (i.e., optimising a thermal network for simulation).

Figure 4 presents principles of both even and uneven space discretisation procedures. For example in the five-node case, the even discretisation consists of three equal internal thermal nodes and two equal surface nodes (with space increment of $\Delta x/2$). In the uneven gridding case presented in Paper III, the external surface node represents an increment of $\Delta x_0/2$, and all subsequent nodes are defined according to a geometric series. Two main parameters for a rational uneven gridding approach are the surface Biot number (Bi_s), and the space increment ratio (q). The surface Biot number (a ratio between conduction and surface convection resistances) is defined as

$$Bi_s = \frac{h\Delta x_0}{\lambda} \quad , \tag{6}$$

The space increment ratio between two adjacent increments is defined as:

$$q = \frac{\Delta x_{i+1}}{\Delta x_i} \quad , \tag{7}$$

where Δx_{i+1} is the subsequent space increment after Δx_i [m].

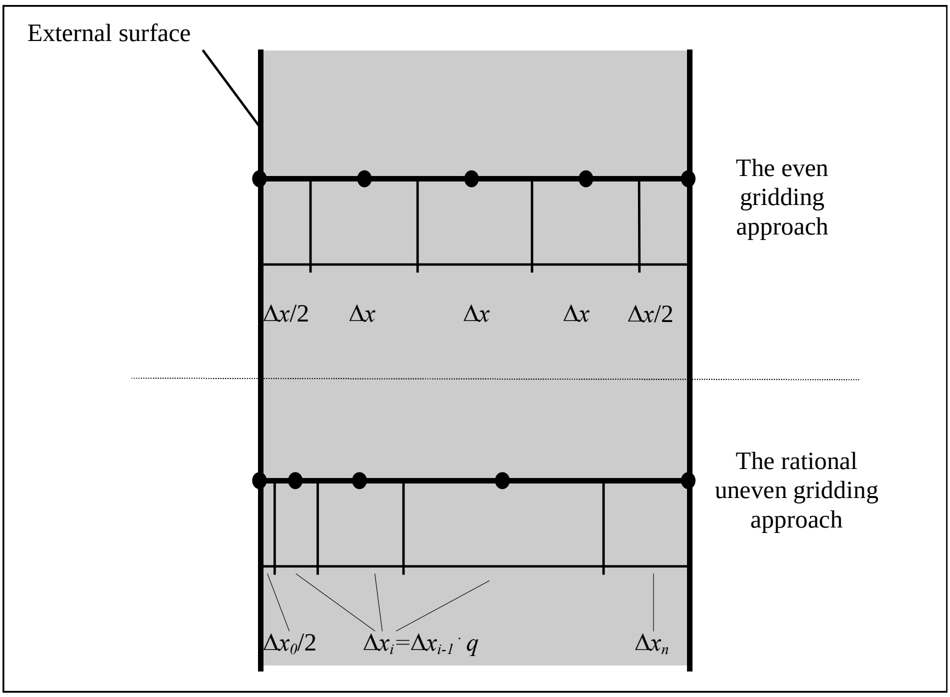

Figure 4. The even and the rational uneven gridding procedures.

Adopting the uneven gridding approach reduces the simulation time for transient heat transfer processes without any noticeable loss of accuracy because a fine grid close to a surface assures reasonable accuracy level, while a coarse grid further away from a surface reduces the number of necessary thermal nodes. For example, the results presented in Paper III indicate that simulation time can be reduced significantly when applying the rational uneven gridding compared to even gridding for a homogenious slab subjected to a sinusoidal external temperature. The reduction in simulation time varied from 44 % to 86 % with slab thicknesses of 0.12 m and 0.39 m, respectively.

2.4.5 An Improved Progressive Refinement Method (Paper IV)

Thermal radiation plays an important role in the energy balance and thermal comfort of a building, yet current methods of solving thermal radiation are deficient. The solutions are often too inaccurate because of large grids or too slow because of inefficient algorithms. Therefore, a new method for solving thermal radiation (IPRM) has been developed which provides a rational compromise between speed and accuracy (Paper IV).

The basic theory of thermal radiation processes within a building has been well known for many years, and Figure 5 shows the basic definitions of different thermal radiation variables. Irradiation to a surface is a cumulative radiation from it's environment. Radiosity consists of the reflected proportion of irradiation and the emissive power of the surface. Thermal radiation is taken into account in BUS++ by including surface net radiation components in the source term of the energy balance equation (5).

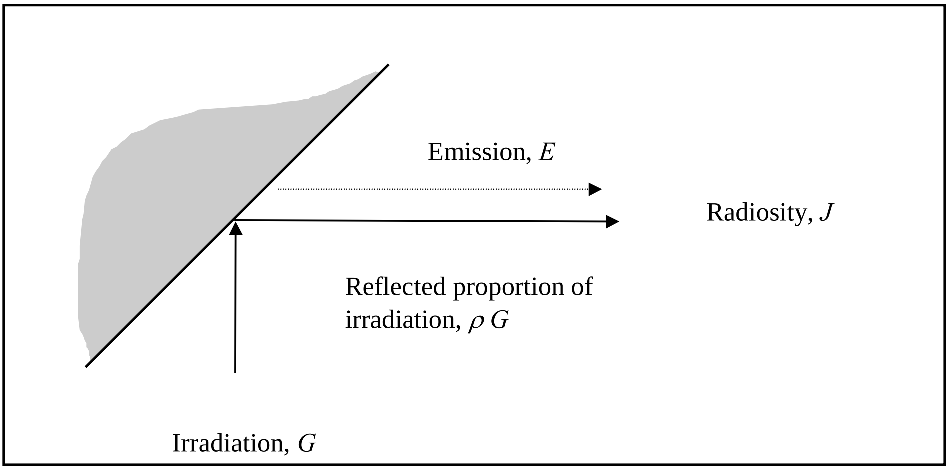

Figure 5. The basic definitions of different thermal radiation variables of a surface element.

Assuming opaque, grey and diffuse surfaces, the radiation heat transfer between surfaces (or parts of surfaces) in an environment can be described with the following set of equations:

$$\begin{bmatrix} 1-\rho_1 F_{1-1} & -\rho_1 F_{1-2} & \dots & -\rho_1 F_{1-n} \\ -\rho_2 F_{2-1} & 1-\rho_2 F_{2-2} & \dots & -\rho_2 F_{2-n} \\ \dots & \dots & \dots & \dots \\ -\rho_n F_{n-1} & -\rho_n F_{n-2} & \dots & 1-\rho_n F_{n-n} \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ \dots \\ J_n \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ \dots \\ E_n \end{bmatrix} \qquad (8)$$

The Progressive Refinement Method has originally been developed and utilised in the field of computer graphics (Foley et al. 1994). In this thesis, an Improved Progressive Refinement Method (IPRM) is applied to solve the surface radiosities (J) in a room (Paper IV). In contrast to the traditional radiosity method used in building simulation tools, the IPRM *shoots* the radiosity from a surface or a part (patch) of a surface into the environment (Fig. 6). After a patch's radiosity has been shot, another patch is selected. A patch may be selected to shoot again after new irradiation has been shot to it from other patches. When a patch is selected again, only the amount of radiosity that the patch has received since last time is shot. Rather than choose patches in random order, the patch that has the most energy left to radiate is chosen and the algorithm iterates until the desired tolerance is reached (Foley et al. 1994).

Figure 6 illustrates the iterative nature of the IPRM. Initially, all patches have delta radiosities equal to their emissive power. Let us assume that the patch *i* has the greatest emissive power that will make the most difference in the radiation system. Therefore, the effect of patch *i* on all other patches will be updated. As a result of this updating, patch *i* will have no radiosity left to radiate (i.e., delta radiosity of patch *i* will be equal to zero), and all other patches will have an increase in their delta radiosities caused by patch *i*. Let us then assume that for the second iteration loop patch *j* has the greatest delta radiosity. After this second iteration loop, delta radiosity of patch *j* will be equal to zero, and delta radiosities of all other patches will have an increase caused by patch *j*. Similar updating will take place during the next iterations, and this iterative solution can be continued untill a desired accuracy level is reached.

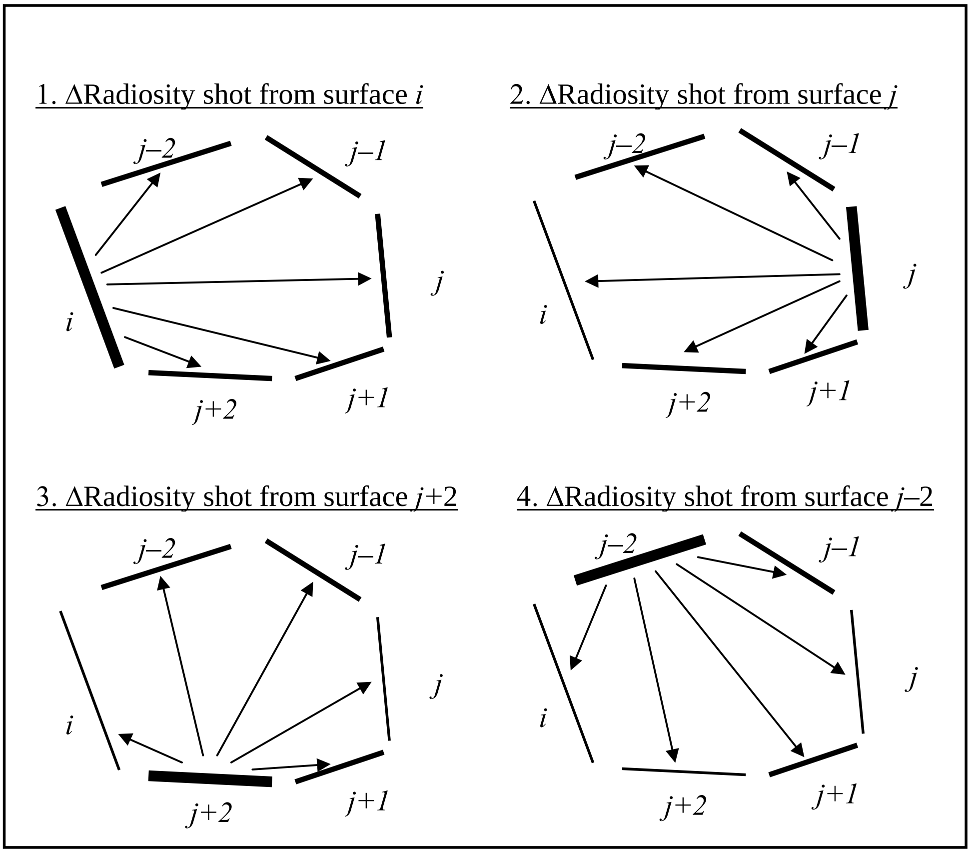

Figure 6. Procedure for shooting delta radiosities iteratively from surfaces according to the Progressive Refinement Method.

After solving the surface radiosities, the net radiation exchange at a surface can be evaluated. It is equal to the difference between the surface radiosity and irradiation and may be expressed as (Incropera and DeWitt 1990):

$$q_i = A_i \, (J_i - G_i) \, . \tag{9}$$

When compared with the matrix radiosity method, IPRM appears to be about ten times faster. In addition, IPRM enables the simulation of radiation gradients over a single surface with less computer memory requirement and without any appreciable loss of accuracy (Paper IV).

3. Validation and application

When developing building simulation routines, it is necessary to include all the important physics for accuracy, but neglect less important effects to keep the model and solution times manageable. Therefore, validation of the simulation package is crucial to determine its accuracy and range of applicability. Validation means to verify that the calculated solution is sufficiently accurate to serve the purposes for which the model was constructed (Bloomfield 1999). The solution is not the definitive answer but, rather is limited by the uncertainties in the model. Through the validation process, the uncertainty of the model can be estimated.

Three types of tests have been most commonly used to validate building simulation programs. One is analytical verification, another is empirical validation, and the third is comparison with other simulation programs. The analytical technique is severely limited because of the small range of problems for which exact analytical solutions can be formulated. The advantages of inter-model comparisons are that they are simpler than the other techniques, and any complexity of the building or any climate regime can be chosen; the principal disadvantage is that there is no absolute truth model against which to compare the predictions. Empirical validation has the greatest potential for assessing whether the approximations and operations in the model are adequate to predict the measured building response (Bowman and Lomas 1985).

All three types of validation tests have been conducted to validate the air flow and heat transfer routines in BUS++. These tests are described in detail in Paper V and only an overview is presented here. Table 1 summarises the typical differences between the simulation and validation data for each test and shows good agreement, especially for the analytical and inter-model validation tests. Table 1 shows that most of the tests validate the air flow and heat transfer routines separately, while the fireplace validation test validates coupled air flow and heat transfer. The fireplace test is the most rigorous validation test, and it is described in detail in Paper V because it is unique in the literature. Figure 7 shows the measured and simulated overall heat power output from the fireplace to the test chamber during a 24 h period. The difference between the measured and simulated peak heating rates is less than 100 W (about 7 %), and the average deviation between the measured and simulated heat power output values is 65 W

(6.7 %). The agreement is very good considering the complexity of coupled air flow and heat transfer within a wood burning fireplace. In order to calculate the heat output from the fireplace, the model must accurately calculate the buoyancy driven air flow through the fireplace as well as the multi-mode heat transfer within the stove and between the stove and the test room (i.e., convection heat transfer to the room air and radiation heat transfer to the room surfaces).

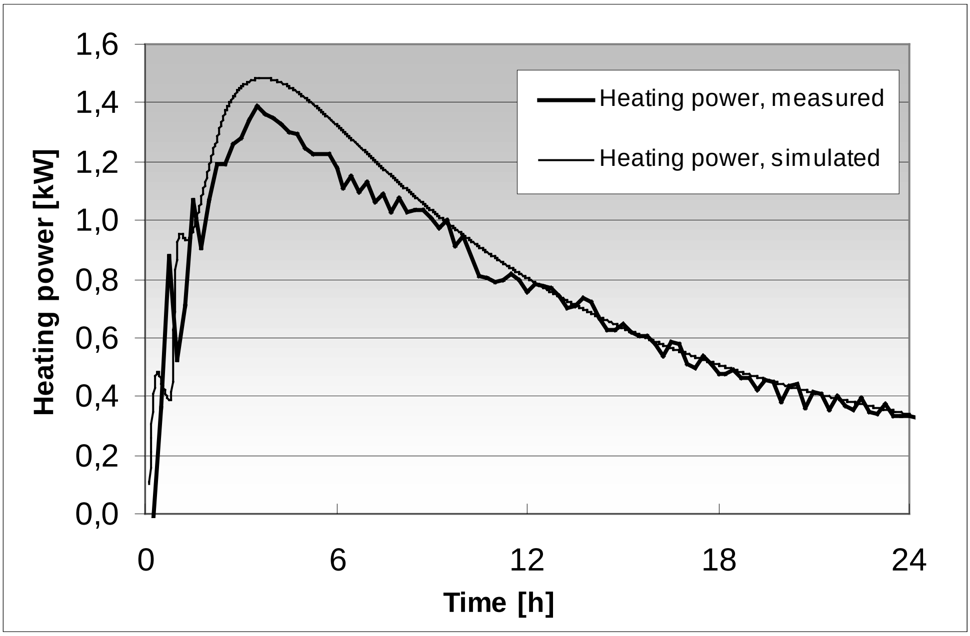

Figure 7. The measured and simulated heat output rates from the fireplace to the test chamber during a test run of 24 h (Paper V).

Based on the validation results in Paper V, BUS++ can be used to predict the thermal behaviour of building components and to calculate air flow rates through ventilation ducts, building envelopes and large openings. However, the results also show the importance of the assumptions and limitations related to these routines and models. For example, since the network approach is adopted, time and space discretisation for thermal simulations must be carefully considered as shown in Paper III. In addition, as shown in the experimental air flow and heat transfer validation cases (Paper V), both boundary conditions and component input data must be carefully defined in order to realise accurate simulation results.

Table 1. Summary of the typical percent differences between the simulated and reference results of each test case (Paper V).

Test type	Air flow	Heat transfer
Analytical	< 1 %	2 %
Inter-model	2 %	1 %
Empirical	10 %	7 %

4. Discussion

A new assembly of simulation routines for evaluation of both ventilation and heat transfer processes of buildings is succesfully implemented and validated. This new building simulation tool is based on the discretization and solution of the fundamental physical equations for mass, momentum, and energy balance. This allows a flexible solution of coverning equations upto a desired accuracy level – in both steady-state and dynamic time domain.

4.1 Limitations

The air infiltration and ventilation processes are solved utilising an iterative approach to solve the mass and momentum equations. There are four potential sources of error related to this approach:

1. All flow elements (ducts, fans, cracks, etc.) need to be described by an empirical flow model giving the necessary fluid flow information for the solver (i.e., the relationship between the mass flow rate and the pressure loss across the flow element). This information is not always known with a high accuracy, which can lead to a large uncertainty in the numerical results.

2. When a building is discretised for the solver, a complete and instant mixing of air in the calculation network is assumed. This assumption is not appropriate when there is significant thermal stratification of room air, as may occur with natural or displacement ventilation systems.

3. Three driving forces of air are introduced – fans, external wind, and thermal buoyancy – and all of these three forces can be estimated only with a limited accuracy. In practical cases, the most difficult component is the external wind. This is because the building surroundings strongly affect the flow pattern of wind and there is no reliable and effective method for evaluating the value of wind pressure coefficients for complex cases. In addition, thermal buoyancy can cause high uncertainties, especially together with stratification of room air.

4. The fourth source of error is related to the iterative solution method adopted in this application. As a result of the iterative solution method, the mass and momentum conservation equations can be fulfilled only within a limited accuracy level. This is due to the limited number of digits available on digital computers, but mainly due to the convergence criteria that must be selected for the solution. If this criteria is too large, the solution errors can become noticeable; but if the criteria is too tight, the solution procedure will slow down.

Despite the limitations mentioned above, this new application BUS++ is capable of solving a wide range of air flow test cases effectively and accurately, as demonstrated in Papers I, II and V.

Evaluation of the thermal behaviour of a building and building structures is based on discretisation and solution of the heat balance equations. This approach allows the solution of multi-mode heat transfer (i.e., thermal convection, conduction, and radiation). Thermal convection is modelled by giving the surface heat transfer coefficients as input data. Thermal conduction is estimated using a thermal network, where nodes with thermal capacity are connected with thermal conductances. Thermal radiation is solved by calculating the net thermal radiation components for each surface node that exchanges radiation within a space.

There are two potential sources of error for the thermal simulation. The first one is related to the network approach. When adopting the network approach, the temperature gradient within a single thermal node is assumed to be zero. Secondly, all material properties are assumed to be constants during the whole simulation process. This can lead to significant errors for materials with thermal properties that are strongly dependent on temperature.

4.2 Main results

There are five main results presented in this thesis, which increase the general knowledge in the area of building simulation. The first new result is a successful implementation of an existing network solution method for air infiltration and ventilation processes (Paper I). (The solution method was originally developed by Juslin and Siikonen (1983) for nuclear power plant training simulator.) The second major result is the integration of ventilation and heat transfer routines, and implementation of a sophisticated sparse matrix solution solver in the core of the new simulation tool BUS++ (Paper II). The third new development is a rational method for generating a numerical grid, which provides compromise between accuracy and computational effort, when modelling transient heat conduction in plane slabs (Paper III). The fourth major contribution of this study is the implementation of the Improved Progressive Refinement Method, which allows a more realistic evaluation of non-uniform thermal radiation in a space, while requiring less computer time and memory (Paper IV). In addition to these four main results, a new validation test set for building energy analysis tools is compiled and shown to be in good agreement with the results obtained by BUS++ (Paper V). Among these test cases new empirical test data quantifying coupled air flow and multi-mode heat transfer in a wood-burning fireplace is presented. These data can be used to validate models that calculate coupled air flow and heat transfer.

4.3 Generality and applicability of the results

The new building simulation routines presented in this thesis can be used when solving the discretised mass, momentum, and heat balance equations. Therefore, the results are general and applicable for all simulation tools and environments based on similar network assumption. However, the applicability of the methods should be considered in each case. For example, the Improved Progressive Refinement Method can be applied in all simulation tools which calculate radiation heat transfer using view factors. The new gridding method can be utilised in all simulation tools, which allow the free generation of a thermal network.

The validation study (Paper V) shows that the routines implemented in the new building simulation tool, BUS++, can be applied to study ventilation and thermal processes in buildings. The effect of various air infiltration and ventilation parameters (wind, internal and external temperatures, and properties of air flow elements) on pressure distributions and air flow rates can be estimated. In addition, interaction between ventilation and thermal processes can be estimated. Results of the rational thermal network generation routine (Paper III) and the

Improved Progressive Refinement Method (Paper IV) can be utilised, for example, when evaluating transient thermal behaviour and thermal inertia of heating devices and building structures.

4.4 General remarks and future outlook

This work is limited to development of air flow and heat transfer routines, and therefore development of all simulation tool interfaces, post-processors and component databases are excluded. However, during the validation procedure several test applications were coded. It was noticed that as the complexity of the test case increased, the importance of user-interfaces increased. Therefore, it is strongly recommended to develop a powerful user-interface for this tool in such a way that the full potential of the developed simulation routines can be utilised in the future. The most important developments are (i) a building description routine, (ii) a building component database, (iii) an HVAC component database, (iv) a weather database, (v) occupation behaviour schedules, and (vi) post-processor features.

5. Summary

The objective of this study was to implement and evaluate air flow and heat transfer routines to allow a better and more thorough understanding of thermal and ventilation performance of buildings. The work was limited to the development of simulation routines, focusing on the methods of predicting air infiltration and ventilation processes, and multi-mode heat transfer within and between different building structures. The theory behind these routines is mainly presented in scientific articles (Papers I to IV). A set of test cases, together with the results obtained by the routines implemented in a new building simulation tool BUS++, is presented in a separate paper (Paper V). This thesis summarises the results and links these separate articles together.

The selected calculation method for air infiltration and ventilation process has proven to be a robust and powerful choice when predicting pressure distribution and mass flow rates in a building. There is an excellent agreement between the analytical and simulated results in all the air flow test cases (Paper V). The tests also indicate the suitability and power of the adopted sparse matrix solution method implemented in BUS++.

In the field of thermal simulation, two new methods were implemented and validated. The first one deals with a rational method for establishing the distribution of nodes when modelling transient heat conduction in plane slabs. The test results show that a powerful compromise between accuracy and computational effort can be obtained when adopting an uneven gridding approach. However, more work is needed to better understand the influence of the two dimensionless parameters introduced (Paper III). The second new method deals with thermal radiation within a space. This new method (Improved Progressive Refinement Method) allows a more realistic evaluation of non-uniform thermal radiation within a space to a desired accuracy level, while requiring less computer time and memory (Paper IV). In the field of numerical validation, a significant validation data set (including new experimental data) was compiled and applied to verify the coupled air flow and heat transfer routines in BUS++ (Paper V).

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Title

Implementation and evaluation of air flow and heat transfer routines for building simulation tools

Abstract

Environmental, epidemiological and economical reasons increase the pressure to design, construct and maintain better buildings in the future. Therefore, a new assembly of simulation routines for predicting both ventilation and heat transfer processes of buildings were studied. The work was limited to implementation and evaluation of new air flow and heat transfer routines for building simulation tools. Development of simulation tool user-interfaces, post-processors and component database have all been excluded.

The simulation routines were implemented in a new building simulation tool BUS++, which was based on discretisation and solution of mass, momentum, and heat balance equations. Ventilation fans, external wind and thermal buoyancy were included as driving forces for air infiltration and ventilation process. Two completely new routines were developed and implemented to obtain more reliable estimations of dynamic and multi-mode heat transfer covering thermal convection, conduction, and radiation. The first new routine focused on defining a rational thermal calculation network, and the second one concentrated on simulation of thermal radiation in a room. Finally, a rigorous set of tests were conducted to validate the air flow and heat transfer routines implemented in BUS++. The test set included commonly utilised analytical verifications and inter-model comparisons as well as completely new empirical validation test cases.

The new rational gridding method reduced simulation times by 44 % to 86 % in a typical slab test case with a cyclic excitation, and the new routine for thermal radiation was up to ten times faster than the conventional matrix radiosity method. In addition, the simulation and validation data showed good agreement, especially for the analytical verifications and inter-model comparisons with typical differences less than 2 %. Despite these promising results, more research work is needed to further develop the simulation routines. In the future, special attention ought to be paid to simulation tool user-interfaces to facilitate full utilisation of the simulation tool by a wide range of users.

Keywords

air conditioning, HVAC systems, heat transfer, air flow, air quality, buildings, simulation, BUS++, networks, data processing

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