External coupling between building energy simulation and computational fluid dynamics

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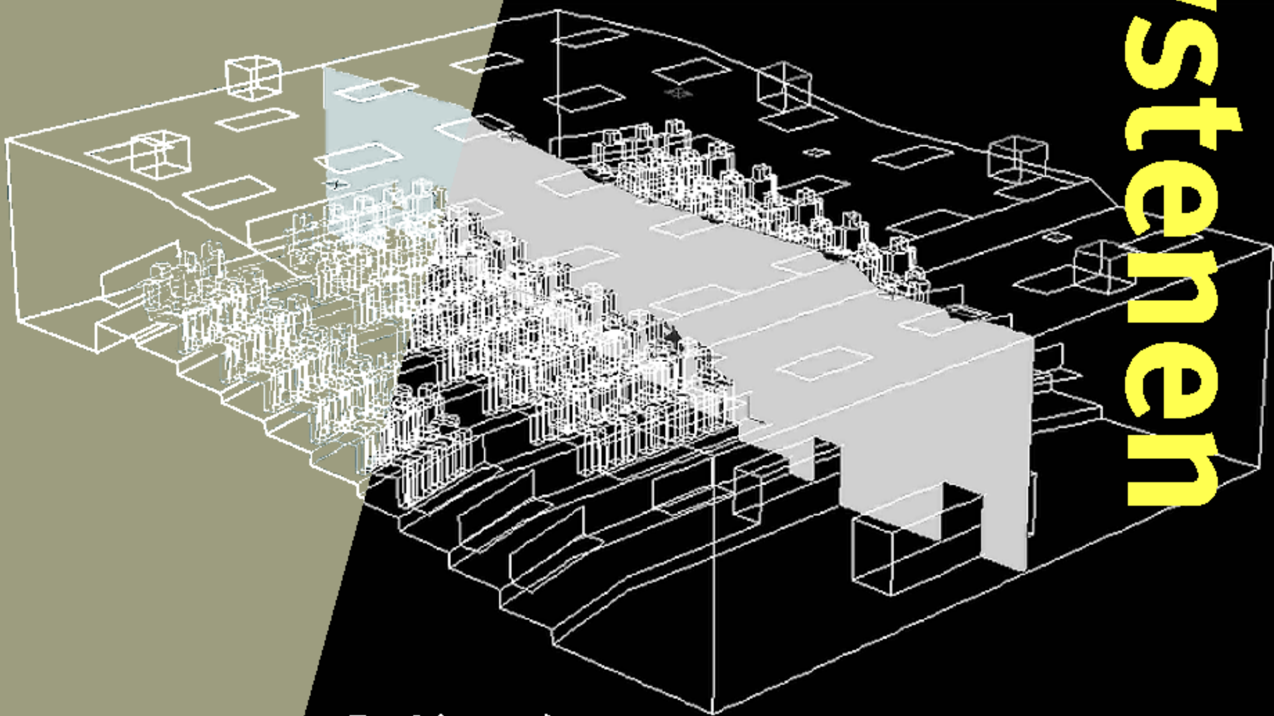

Ery Djunaedy

External coupling between building energy simulation and computational fluid dynamics

/ faculteit bouwkunde

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PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op woensdag 20 april 2005 om 16.00 uur

door

Ery Djunaedy

geboren te Aceh, Indonesië

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Dedication

For the ultimate trust she gave
in believing a (then) young student
to build our life together
from scratch
despite the uncertainty of the future

For the unquestioning loyalty
to hold on firm to the sail of our family
despite the nearly-not-enough livelihood that I can provide

For the continuous flow of love
despite so little attention I can give her back
in my hectic life as a junior researcher

As a milestone for our 10th anniversary,
I dedicate this thesis to:

my friend,
the other half of my soul,
my beloved wife,

Lintang Karainan

Acknowledgement

My colleague jokingly remarked that by doing a PhD, “you better get a PhD degree, or otherwise you will get ***p***ermanent ***h***ead ***d***amage”, referring to the risk of ruining my own life (and of course my family) should I not succeed in completing the research. In the end of my PhD study, looking back to that joke, I think it could have been worse than that: I could get a degree ***and*** permanent head damage.

Acknowledgement is always my favorite section every time I read a PhD thesis, whatever the field of study is. But not until this time I can really appreciate how important it is to write acknowledgment in a PhD thesis. These are the people who help me to move forward in my research, stay focus in my work to meet the targets, but more importantly these are also the people who help me to keep my sanity intact during the highs and lows of the four years study, and help me define a meaning in the times of life under constant risk of falling apart.

I am indebted to Prof. Jan Hensen who has trusted me to take up the vacancy as a PhD candidate. I was then a very young researcher, who has just completed my MSc, with a few publications to support my application for the vacant position. Started out with some email correspondence between Singapore and Eindhoven, followed by an interview in Eindhoven, I was suddenly realized that I was going to start my PhD study in May 2001. With this and many other instances he has taught me the meaning of giving somebody a chance.

On the professional level, he is more than any PhD students can hope for a supervisor. Not only he guided me in the course of my research, but more importantly he kept my focus to the goal. He also pushed me to the limits of my ability with his demanding targets. This proved to be useful in nurturing my skill in managing deadlines (and the associated stress that comes along).

While many PhD candidates in TU/e rarely see their first promotor (even if they can, they have to make an appointment through the secretary), I am very lucky to be able to knock on the door and steal my professor’s time for a couple of minutes. These couple of minutes, however, in many cases turned out to finish considerably longer.

On the personal level, he always pays attention to my personal (and family) matters. He always insisted that I clear my days-off regularly and spend some time with my family. My family will always remember the family gatherings and the dinners that follow. My children would never forget the “red van” trips with Uncle Jan (we used different vans, but I do not know why the red one sticks to their mind).

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I would like to thank the Netherlands Institution for Scientific Research (NWO) that provided the financial support for me to visit Purdue University in the USA.

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I am also honored to have Prof. Joe Clarke, Prof. Henk van der Ree and Prof. Anton van Steenhoven as examiners who have read the final draft of this thesis. I am grateful for their constructive comments and criticisms to this PhD work.

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To my parents, who always support my decision to continue my study, thanks for the unconditional support. They, and also my mother in-law, have helped me to take care of my family when I need to leave them back home in Indonesia. To my sons Hanif, Abdih and the newborn Sajid, may these four years become an important part of your upbringing.

To Lintang my wife, to whom this thesis is dedicated, no words of thanks could describe my gratefulness to you. The ten years of marriage would not be the same without your patience, your tears, your sense of humor, your courage, your smile, and your enduring love.

> "This is by the Grace of my Lord to test me whether I am grateful or ungrateful!"
>
> The Quran 27:40
>
> "My Lord! Inspire and bestow upon me the power and ability that I may be grateful for Your favours which You have bestowed on me and on my parents, and that I may do righteous good deeds that will please You, and admit me by Your mercy among Your righteous servants."
>
> The Quran 27:19
>
> ".. and the end of their prayer is: 'All the praises and thanks are to Allâh, the Lord of all that exists'"
>
> The Quran 10:10

27 February 2005

Ery Djunaedy

Table of contents

Publications

The work in this thesis has partially been published in the following publications.

In refereed journals

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2005. "External coupling between CFD and energy simulation: implementation and validation", *ASHRAE Transactions*, Vol. 111.

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2004. "Selecting an appropriate tool for airflow simulation in buildings", *Building Services Engineering Research and Technology*, Vol. 25, No. 3, pp. 289-298.

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2003. "Toward External Coupling of Building Energy and Airflow Modeling Programs", *ASHRAE Transactions*, Vol. 109, No. 2, pp. 771-787.

In conference proceedings

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2004. "Comparing internal and external run-time coupling of CFD and building energy simulation software", in *Roomvent 2004,* Proceedings of the 9th International Conference on Airflow in Rooms, Coimbra, Portugal, pp. 393-396.

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2003. "Development of a guideline for selecting a simulation tool for airflow prediction", in *Building Simulation 2003*, Proceedings of the 8th International IBPSA Conference, Eindhoven, Netherlands, pp. 267-274.

Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. 2002. "Towards a strategy for air flow simulation in building design", in *Roomvent 2002,* Proceedings of the 8th International Conference on Airflow in Rooms, Copenhagen, Denmark, pp. 393-396.

In reports and professional magazine

Djunaedy, E. 2004. *Validation of external coupling between CFD and energy simulation*, FAGO Internal Report 04 - 31, FAGO, Fac. Bouwkunde, Technische Universiteit Eindhoven, Netherlands.

Djunaedy, E. 2004. *Implementation of external coupling between CFD and energy simulation*, FAGO Internal Report 04 - 29, FAGO, Fac. Bouwkunde, Technische Universiteit Eindhoven, Netherlands.

Djunaedy, E., Hensen, J., Loomans, M. 2003. "Lucthstromingssimulatie – een doordachte keuze ", *TVVL Magazine*, Vol. 32, No. 12, pp. 66-68.

Summary

Building function has evolved from its primitive and essential function to provide shelter for human against outside environment. With the pressure from both the demand side (human's need) and the supply side (technology to meet the need), building nowadays consists of complex dynamic interactions between its components. So complex the system is, that it is only by taking into account its dynamic interactions that a complete understanding of building behavior can be obtained. Optimizing the building and the system as a whole is not the same as optimizing the subsystems or components. This has moved the research direction towards integrated multi-domain building simulation.

This thesis shows the viability of the external coupling method in achieving the integrated multi-domain building simulation tools. Different from the internal coupling method where the domain expansion always means writing new codes into the existing program, the external coupling combines two or more programs during run time. Using the external coupling method, the code changing can be kept to minimum and the development in any domain can be made available to other domains immediately, provided the communication protocol between the domains has been established.

Considering the importance of building energy simulation (BES) in the building design process and the current trend of wide-spread use of computational fluid dynamics (CFD) simulations, these two domains were selected as the basis of the work in this thesis. The coupling procedure developed involves the two (BES and CFD) domains.

In the rapid developments of computer technology, many simulation tools are available for use, which falls on a very wide spectrum in terms of sophistication and applicability. The process of selecting which tool(s) to be used for a certain problem is most of the time abstract and subjective. This thesis proposes a guideline to assess the necessity of coupled simulation, which can be used also as a guideline to select the appropriate tool(s) for a certain problem.

Sensitivity analysis is used in the guideline to select the appropriate complexity and resolution of the simulations. This guideline considers the whole range of available tools and defines logical steps on how to select the appropriate tool for a certain problem. Although it was (initially) developed for airflow domain, this guideline can also be applied to any domain.

The main contribution of the guideline is that it tries to make a logical scheme to what is usually an abstract and subjective endeavour.

The working prototype of external coupling between BES and CFD has also been implemented. Generic requirements for BES and CFD packages to be able to use external coupling has been formulated. Along with the examples, the generic requirements allow anybody to replicate the development process and use any other BES or CFD package for the coupled simulation.

The quality assurance was conducted through a series of validation studies. The result shows that the external coupling method could produce the result as good as the internal coupling. Having achieved this, it is only a matter of time before it gets better because the development in any domain can be immediately made available to other domains by using the external coupling method.

An application study was carried out to highlight the benefits of the coupled simulation. The use of the guideline has been demonstrated in the application study, where the guideline can assess the need for coupled simulation for the problem. The results of the coupled simulation also confirm the benefits of coupled simulation to get a better and more accurate design decision.

Samenvatting

De functie van gebouwen is geëvolueerd vanuit een primitieve en essentiële functie om de mens te beschermen tegen het buitenmilieu.Met toenemende druk aan zowel de vraagkant (de behoefte van de mens) als de aanbodzijde (technologie om aan die behoefte te voldoen), bestaan er in gebouwen nu dynamische interactie tussen de verschillende componenten. Het totale systeem is zo complex dat alleen door met de dynamische interacties rekening te houden een volledig inzicht in het gebouwgedrag kan worden verkregen. Optimaliseren van het gebouw en het systeem als geheel is niet hetzelfde als het optimaliseren van componenten of subsystemen. Dit heeft geleid tot onderzoek naar integrale multi-domein gebouwsimulatie.

Dit proefschrift toont de levensvatbaarheid van externe software koppeling met als doel integratie van multi-domein gebouwsimulatie hulpmiddelen. Anders dan bij interne koppeling, waarbij domeinuitbreiding altijd inhoudt dat nieuwe broncode aan een bestaand programma moet worden toegevoegd, worden hierbij twee of meer programma's alleen gedurende de executie extern gekoppeld. Bij gebruik van externe koppeling, kunnen verandering van de broncode tot een minimum beperkt worden. Tevens kunnen ontwikkelingen in afzonderlijke domeinen onmiddellijk gebruikt worden in de andere domeinen, op voorwaarde dat er een communicatie protocol tussen de domeinen is vastgesteld.

Gelet op het belang van energiesimulatie (BES) in het ontwerpproces van gebouwen en de toenemende wijdverbreide toepassing van numerieke stromingsmodellen (CFD), werden deze twee domeinen geselecteerd als uitgangspunt voor het werk beschreven in dit proefschrift. De ontwikkelde koppelingsmethode betreft de twee (BES en CFD) domeinen.

Binnen andere snelle ICT ontwikkelingen is er ondertussen een grote keuze aan simulatie software met een brede range qua verfijning en toepasbaarheid. Het keuzeproces waarbij geselecteerd wordt welk(e) hulpmiddel(en) gebruikt moet(en) worden voor een bepaald probleem is grotendeels abstract en subjectief. Dit proefschrift presenteert een richtlijn waarmee de noodzaak van gekoppelde simulatie kan worden beoordeeld en die tevens gebruikt kan worden om het juiste hulpmiddel voor een bepaald probleem te selecteren.

In deze richtlijn wordt gevoeligheidsanalyse gebruikt de juiste complexiteit en resolutie van de simulatie modellen te selecteren. Deze richtlijn houdt rekening met de gehele reeks van beschikbare hulpmiddelen en omschrijft logische stappen om het aangewezen hulpmiddel voor een bepaald probleem te selecteren. Hoewel het (aanvankelijk) voor het domein van luchtstromingen werd ontwikkeld, kan deze richtlijn ook op andere domeinen worden toegepast. De belangrijkste vernieuwing van de richtlijn is dat deze probeert om een logisch schema te maken van wat gewoonlijk een abstracte en subjectieve activiteit is.

Er is een werkend prototype van externe koppeling tussen BES en CFD geïmplementeerd. Er zijn generieke vereisten voor BES en CFD software vastgesteld ten aanzien van het gebruik van externe koppeling. In combinatie met de gepresenteerde voorbeelden, kunnen deze generieke eisen worden gebruikt om het ontwikkelingsproces te herhalen en andere BES en CFD software voor gekoppelde simulaties te gebruiken.

Voor kwaliteitsborging zijn een reeks validatiestudies uitgevoerd. De resultaten tonen aan dat externe koppeling tot een even goed resultaat kan leiden als bij interne koppeling. Dit bereikt hebbende, is het slechts een kwestie van tijd voor externe koppeling beter wordt omdat ontwikkelingen in de afzonderlijke domeinen daarmee onmiddellijk toepasbaar zijn in de andere domeinen.

Om de voordelen van de gekoppelde simulatie te verduidelijken is een toepassingsstudie uitgevoerd. Hierbij wordt ook de keuzerichtlijn gedemonstreerd, waarbij is gebruikt om te beoordelen of gekoppelde simulatie voor het betreffende probleem noodzakelijk is. De resultaten van de gekoppelde simulatie bevestigen ook de voordelen van gekoppelde simulatie om tot betere en nauwkeuriger ontwerpbeslissingen te komen.

Chapter 1

Introduction

This chapter introduces the external coupling method, and shows its location among other methods in the quest for integrated multi-domain building simulation. The advantages of external coupling method are compared with the internal coupling from the development point of view. The reasons to start with energy domain and detailed airflow domain are also discussed. Finally the objectives of this thesis and the thesis layout are presented.

1.1 Analysis tools for building

Building function has evolved from its primitive and essential function to provide shelter for human against outside environment. The occupants demand that the building can provide a suitable environment for whatever they are doing inside the building. Creating an acceptable atmosphere for occupants' activity seems to be the objective of the building design nowadays.

Technology has also changed the way how buildings are built. Our ancestors initially did not have any choice but to accept the condition of the caves they were living in. But technology has changed that condition. Not only we now have the capability to build building in any shape we want, but we also have the capability to control the indoor environmental condition.

With the pressure from both the demand side (human's need) and the supply side (technology to meet the need), building nowadays consists of complex dynamic interactions between its components. Figure 1.1 shows a simplified view of the components and its dynamic interactions.

So complex the system is, that it is only by taking into account its dynamic interactions that a complete understanding of building behavior can be obtained. Furthermore, optimizing the building and the system as a whole is not the same as optimizing the subsystems or components.

Table 1.1 (Morbitzer 2003) shows different tools that can be used in building design. The simple rules-of-thumb and the simple calculation method used to be able to meet the demands of people. Not anymore. The rules-of-thumbs and simple calculations are not enough to predict the performance of our building today. With different demands, and different technology to build the building, the building has become a set of complex processes of mass and heat transfer too difficult to predict its performance by simple rules or calculations.

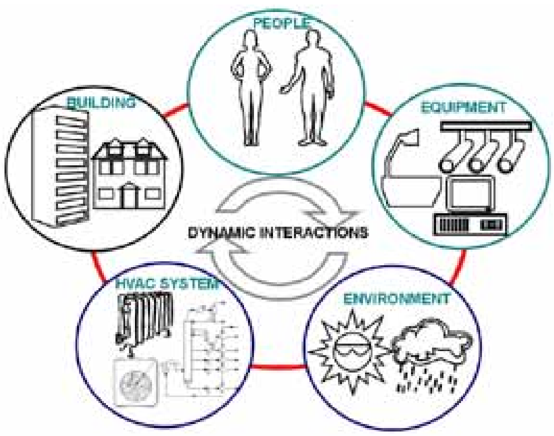


Figure 1.1 Dynamic interaction of building components

Clarke (2001) presented Figure 1.2 to highlight the difference between simple techniques and integrated simulation. The figure shows the annual energy requirements (of a multi-storey hotel) determined for alternative glazing scenarios. The ESP prediction was in stark contrast with the results of simple calculation (RIBA calculator) and of the manual calculation method (taken from CIBSE guide). Both simplified methods lead to the conclusion that there will be an increase in energy consumption if the glazing area is increased from 25% to 60%. The ESP by using the integrated method predicted the contrary (the curve from C2 to C4 in Figure 1.2).

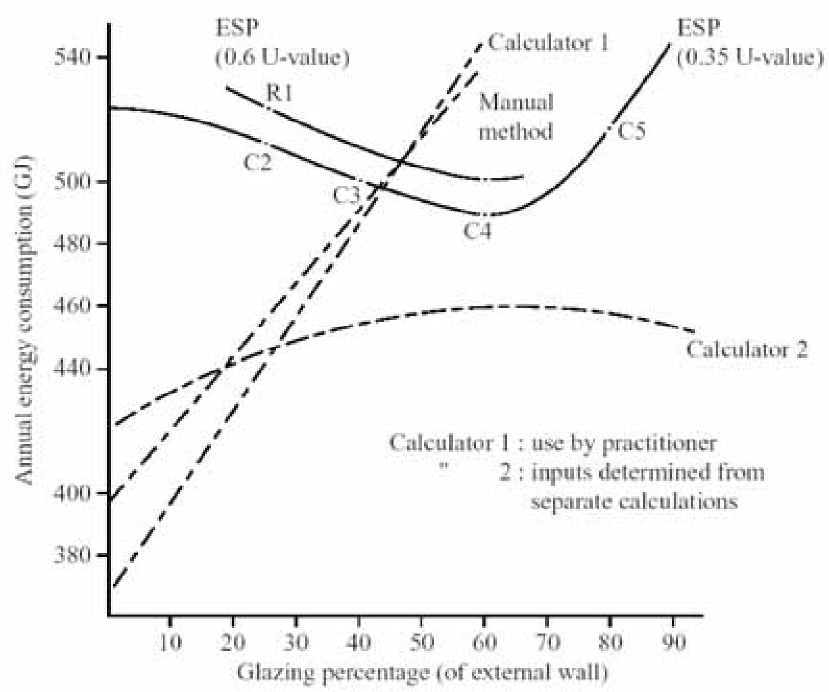


Figure 1.2 Energy consumption predictions by alternative method (graph taken from Clarke 2001)

Table 1.1 Different tools used in building design (Morbitzer 2003)

Methods	Description
Design guidelines or rules of thumb	Do not predict performance but give general design advice
Traditional physical calculation methods (steady state)	Focus on a limited number of physical phenomena in a building in some cases only on one
Correlation based methods	Try to consider all physical aspects that influence a certain building performance; restrictions in design specification and performance assessments
Building simulation	Philosophy of creating virtual building where the user can specify in detail parameters that influence the building performance, with resulting performance predictions that are as close to reality as possible

Although simulation always involves modelling which by definition is a simplification of a real world phenomenon, the models employed by the simulation are getting more and more sophisticated. Not only building simulation is seen as the only alternative tool to predict the behavior of such a complex system like a building, more attention has moved towards ***integrated multi-domain*** building simulation. As Hensen (1991) argued, the optimum performance of the building as a whole cannot be achieved by optimizing the performance of its components separately. The HVAC system cannot be optimized in isolation of the building construction and the occupants' activities in the building. That means the simple single-domain calculation will not suffice to optimize the building as a whole.

1.2 Problem definition

1.2.1 The quest for integrated methods

Building simulation software did not start out as integrated multi-domain simulation package. Clarke (2001) describes the evolution of simulation software as in Table 1.2. The first generation is piecemeal so that there is only a weak coupling between domains. There was no attempt to include all the energy and mass flow paths as in reality, as the intention is only to provide an indication of performance. The result is, however, difficult to interpret as the user has to understand its limitation.

The second generation program has included the building construction dynamics into the calculation while the HVAC system modeling was still done in steady state. Not until the third generation program where the simulation tool can have only space and time as their independent variables, and calculate all other dependent variables. The increase in the computing power has helped to deliver this new generation of simulation programs.

The third generation program has brought a new era of integrated modeling whereby the thermal, visual, and acoustics aspects of performance are considered. What follows are the fourth generation program. In the fourth generation program, the integration of domains is expanded. The interoperability issue has started to emerge in this generation of simulation program.

Table 1.2 Evolution of design tools (taken from Clarke 2001)

<table>
<tr><th>Generation</th><th>Characteristics</th><th>Consequences</th></tr>
<tr><td>1</td><td>Handbook oriented
Simplified and piecemeal
Familiar to practitioners</td><td rowspan="4">Easy to use, difficult to translate to real world, non-integrative, application limited, deficiencies hidden
|
|
|
Increasing integrity vis-à-vis the real world
|
|
|
Deficiencies overt
Easy to use and interpret
Predictive and multi-variate
Ubiquitous and accessible</td></tr>
<tr><td>2</td><td>Building dynamics stressed
Less simplified, still piecemeal based on standard theories</td></tr>
<tr><td>3</td><td>Field problem approach shift to numerical methods integrated modeling stressed graphical user interface partial interoperability enabled</td></tr>
<tr><td>4
And beyond</td><td>Good match with reality
Intelligent knowledge-based
Fully integrated
Network compatible/interoperable</td></tr>
</table>

1.2.2 Two methods for integration

Figure 1.3 shows two possibilities for integrating different domains in building simulation environment (BSE). In the middle of the graph, the BSE contains many modules that represent different domains that are included into the program. The integration of many domains is achieved through code integration where everything is included into a single program. This is what is called by internal coupling.

Figure 1.3 also shows another possibility. There are abundant packages from all domains available. The BSE can simply call an external package every time it needs. This approach is what is called external coupling (further definition is described in Section 2.2.3.2).

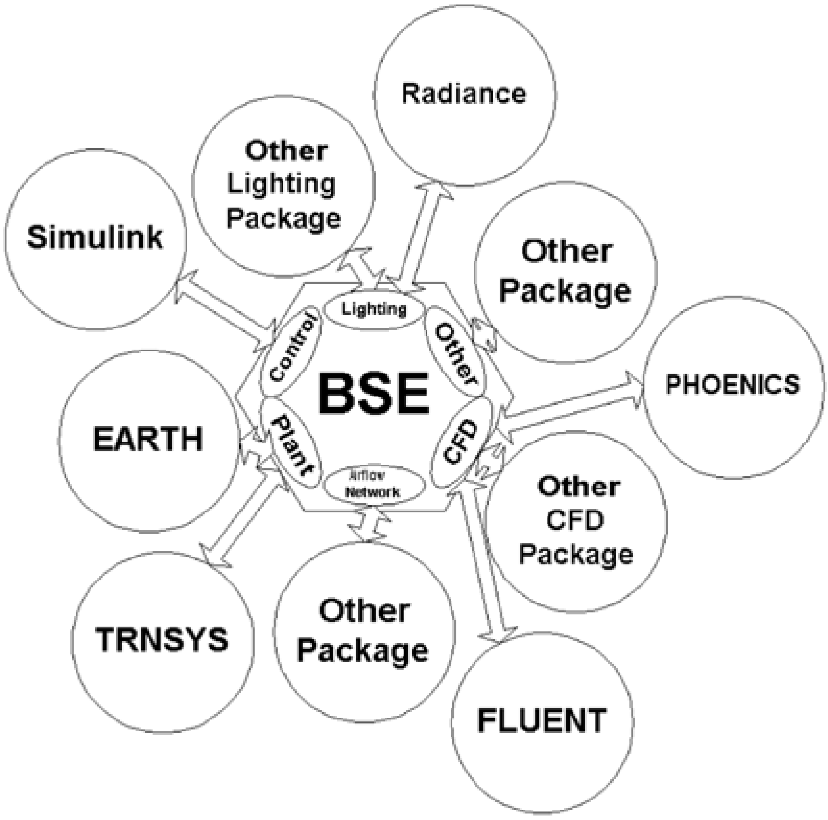


Figure 1.3 Schematic view of a distributed integrated building simulation environment based on an advanced multi-zone building simulation software run-time linked to external software packages

From the development point of view, the main problem of internal coupling is how to ensure the long-term maintenance of the software and associated libraries. Every development in any domain must be transferred in and translated into new source code within the main program.

The cost of developments and maintaining software is expensive. Clarke (2001) described the software development process as used by ESP-r (ESRU 2003). As initially outlined by Maver and Ellis (1982) the process includes several stages: the background research, development of a pilot program, validation of the program, implementation trials, improvement of the software and documentation and then the commercial exploitation. It is important to note that Clarke (2001) pointed out that the resource required at any stage is typically greater than the cumulative resource required in the proceeding stages.

Since no software could possibly include all the possible domains, there is always a chance that sometime in the future there is a need to include a new domain into consideration. With internal coupling, this scenario will be dealt with by including the new domain into the existing program with the consequence that the code needs to be rewritten. Putting this scenario in above scale (as pointed out by Clarke 2001 in the last paragraph), the expensive cost involving the rewriting of the code, and the eventual testing and validating, would immediately be seen.

A better scenario is what is offered by external coupling. All domains can have their own developments in their respective directions. If the BSE needs any of the domains to be included in its calculation, it can always call the best one which is equipped with the latest development in the respective domain.

This is the main advantage that external coupling is going to achieve, i.e. distributed development for integrated simulation. The real developments in a domain are left to the developers in respective domain. When there is a need to couple a certain domain, these latest developments are readily available to BSE with minimum coding work.

This thesis is an attempt to show the viability of external coupling method. The idea is to use existing software and develop a mechanism for the software to communicate to each other.

1.3 Scope of work

This thesis will focus on the coupling between building energy simulation and CFD. In general terms, that is the coupling between thermal domain and detailed airflow domain.

It is probably natural to start from the building energy simulation (BES). By far, it is the most mature building simulation domain. Energy is always the main concern in the building design. The energy crisis in the 70s has boosted the development of energy simulation.

Nowadays, building simulation has even entered an honorable role in building codes throughout Europe. In 2003, the European Commission has issued a directive that requires all of member states by January 2006 to implement national level building codes that requires all (new and existing) building to have an energy performance calculation which includes heating, ventilation, cooling and lighting system (EC 2002). For those reasons, this thesis focuses on BES.

As for CFD, there are several reasons to focus on CFD:

1. Energy simulation is highly sensitive to the airflow definition in the simulation.
2. Energy simulation is also sensitive to the definition of convective heat transfer coefficient (CHTC) used in the simulation. CFD can supply the accurate calculation of CHTC.
3. There is an increasing demand for comfort which can be best predicted using the detailed airflow simulation.
4. There is an increased attention toward CFD simulation in the building industry. Quality assurance of the CFD simulation becomes more critical than before. The coupled BES-CFD simulation can improve the quality of CFD-only simulation.

The coupling of BES and CFD simulation has been studied in various research in recent years, e.g. Negrao 1995, Beausoleil-Morrison 2000, Srebric et al. 2000, Zhai 2003. The coupling (or “integration”) between the two programs is seen as an alternative to achieve better results because the two can provide boundary conditions to each other, and at the same this will overcome their respective limitations.

However, the implementation of the coupling mechanism in the earlier research falls into internal coupling. This is an open opportunity to introduce a new mechanism of coupling between CFD and BES through external coupling.

1.4 Objectives

Based on the above problem definition and scope of work, there are two main objectives for this study.

The ***first objective*** is to generate guidelines with regard to the necessity or applicability of BES, CFD and the cooperative approach in terms of integrated design of buildings and systems. The findings in this line of work will become a basis to approach the implementation of external coupling.

The ***second objective*** is to develop a prototype of cooperative BES and CFD design environment for optimization of building energy performance and indoor environment.

1.5 Thesis layout

Chapter 1 briefly introduces the idea behind this thesis.

Theoretical background will be covered in Chapter 2. The review of literature will put the work outlined in this thesis into the recent developments of building performance simulation tools. In last part of Chapter 2, the methodology used in this study will be outlined.

Chapter 3 describes the proposed guideline to approach the coupled simulation which addresses the first objective of this study. The guideline is a decision support methodology to select the appropriate levels of resolution and complexity (e.g. CFD only, BES and CFD uncoupled, BES and CFD thermally coupled, BES and CFD thermal and flow coupled) for airflow simulation in the context of building design.

Chapter 4 describes the implementation of external coupling between CFD and BES. The earlier implementations from previous research are critically reviewed in the first part of the chapter. In the second part, the implementation of external coupling is described.

The validation of external coupling will be described in Chapter 5. Three cases are presented as validation study to highlight the advantages of external coupling method. One case study is presented to show the potential that can be opened by using the external coupling method.

Chapter 6 presents an application study to show the usefulness of the coupled simulation. Thermo-active concrete core system is selected as the case studied.

Chapter 7 will summarize the conclusions of this study, and also present the direction of future works.

Chapter 2

Theory and methodology

This chapter covers the theoretical background for this thesis. The review of literature will put the work outlined in this thesis into the recent developments of building performance simulation tools. In the last sections, the methodology used in this study will be outlined.

2.1 Introduction

This chapter contains two main sections, the literature review and methodology that will become the basis of the study described in this thesis. The issue of domain integration is critically reviewed in an attempt to put external coupling into the map of software development. Various possibilities of implementations are reviewed and external coupling will be compared with the other methods to highlight its potentials.

The literature review will not cover all topics to be discussed in this thesis. Some of the topics will have the literature reviewed in respective sections in this thesis where they are discussed.

In the last sections the methodology employed by this study to achieve its objective is presented.

2.2 Literature review on domain integration

2.2.1 Different methods for domain integration

As indicated earlier, building systems are so complex that it is not possible to optimize the whole system by optimizing the components separately. The different building components and systems should be simulated simultaneously to optimize the building as a whole. This leads to the increased need of multi-domain simulation tools.

Hensen et al (2004) describes four level of shared development in building performance simulation software, which can also be seen as the method on how different domains are integrated in a simulation environment. These are discussed in the following four sub-sections.

2.2.1.1 Data and process model integration

This is the traditional and most widely used approach. It is based on providing a facility to simulate different sub-domains within the same program. Domain integration is done by including the new domain into the one single program.

Some simulation programs already integrate thermal, ventilation, air quality, electrical power and lighting calculations; e.g. ESP-r (Clarke 2001, ESRU 2003). Integration can also be achieved by merging existing applications and/or hard-wire connections such as was done in the case of TRNSYS (SEL 2004), ISIBAT(CSTB 2004) and is currently being done in the case of EnergyPlus (DOE 2004). Other examples include the SEMPER/ S2 project (Mahdavi et al. 1999), the Building Design Advisor project (Papamichael et al. 1997,LBNL 2003), and Ecotect (SquareOne 2004). Examples that are based on a general simulation environment (Matlab (MathWorks 2004a) or Simulink (MathWorks 2004b)) are Simbad (Hasaundee et al. 1997)and Climasim.

This method is what referred to in Chapter 1 as ***internal coupling***. The integration process is summarized in Figure 2.1.a. Multi-domain simulation is carried out through a single data model and a single program to calculate the results for both domains.

2.2.1.2 Data model interoperation

In this approach, interoperability between programs is achieved on the level of the product (i.e. building and systems) model. Two approaches may be distinguished.

Product model data sharing. Model sharing allows the domain-specific applications to extract the data required for their own purpose from a single data management system that holds both the geometrical and physical parts of the model (Figure 2.1.b). Typical examples are the VABI Uniform Environment, and the COMBINE project (Augenbroe 1994). This approach avoids redundancy of data, but does not entirely prevent inconsistency and still requires an important data management system. When the model is modified, all the other parties have to be informed so that they may download it.

Product model data exchange. Applications exchange a model, in whole or part, by using a data exchange facility generally based on a standardized neutral file format (Figure 2.1.c). While IGES or DXF formats only describe the geometrical part of the model, the Industry Foundation Classes (IFC) by the International Alliance for Interoperability (IAI) includes both the geometrical and the physical parts (Bazjanak and Crawley 1997, Tolman 1999). A recent development in this area is the use of eXtensible Markup Language (XML) as a means to exchange product model data over the world wide web. Product model data exchange simplifies model construction, but, as there is still one model per application, may not the problems of inconsistency (model maintenance).

Citherlet (2001) the data model interoperation method cannot take into account the dynamic of the building as the data exchange or sharing can only happen in the beginning of each application and then the programs run separately. In my opinion, this is only true if the current use of data model interoperation method is considered.

As will be explained below, this method can be used to overcome the limitation of the external coupling method. Data model interoperation can provide an “automatic” model generation to be used for external program to simulate the same problem. I believe that this will be the trend for the future, where data model interoperation is used in combination with external coupling method, for which case the data model interoperation will be able to take into account the dynamics of the building.

2.2.1.3 Process model interoperation

In this approach, interoperation is achieved on the level of the models that describe the thermal, flow, and other physical processes. It has long been realized that especially in the area of system simulation there is still an enormous amount of development work to be done. Therefore it has been suggested that work should be done not only towards the re-use of existing component models (i.e. interoperation at source code level by exchanging component models, e.g. incorporation of TRNSYS and other component models in ESP-r (Hensen 1991)) but also in a more generic way by expressing models in a neutral format.

2.2.1.4 Data and process model co-operation

In this approach, programs provide the facility to link applications at run-time in order to co-operatively exchange information. In early examples, one application controls the simulation and calls the other application(s) when necessary. In this case, only the simulation engine of the coupled program(s) is required and the front-end interface corresponds to the driving application. The main advantage of the coupled approach is that it supports the exchange of information during a simulation contrary to the previous approaches. For example, Janak (1998) has enabled a run-time coupling between ESP-r and the ray-tracing lighting and visualization application Radiance.

This method is what referred to in Chapter 1 as ***external coupling***. The integration process is summarized in Figure 2.1.d. The models for the domains can be created separately, or as pictured in the figure, one of the domains can produce the model for the other domain(s). Two programs are running simultaneously, and exchanging data in a predefined method.

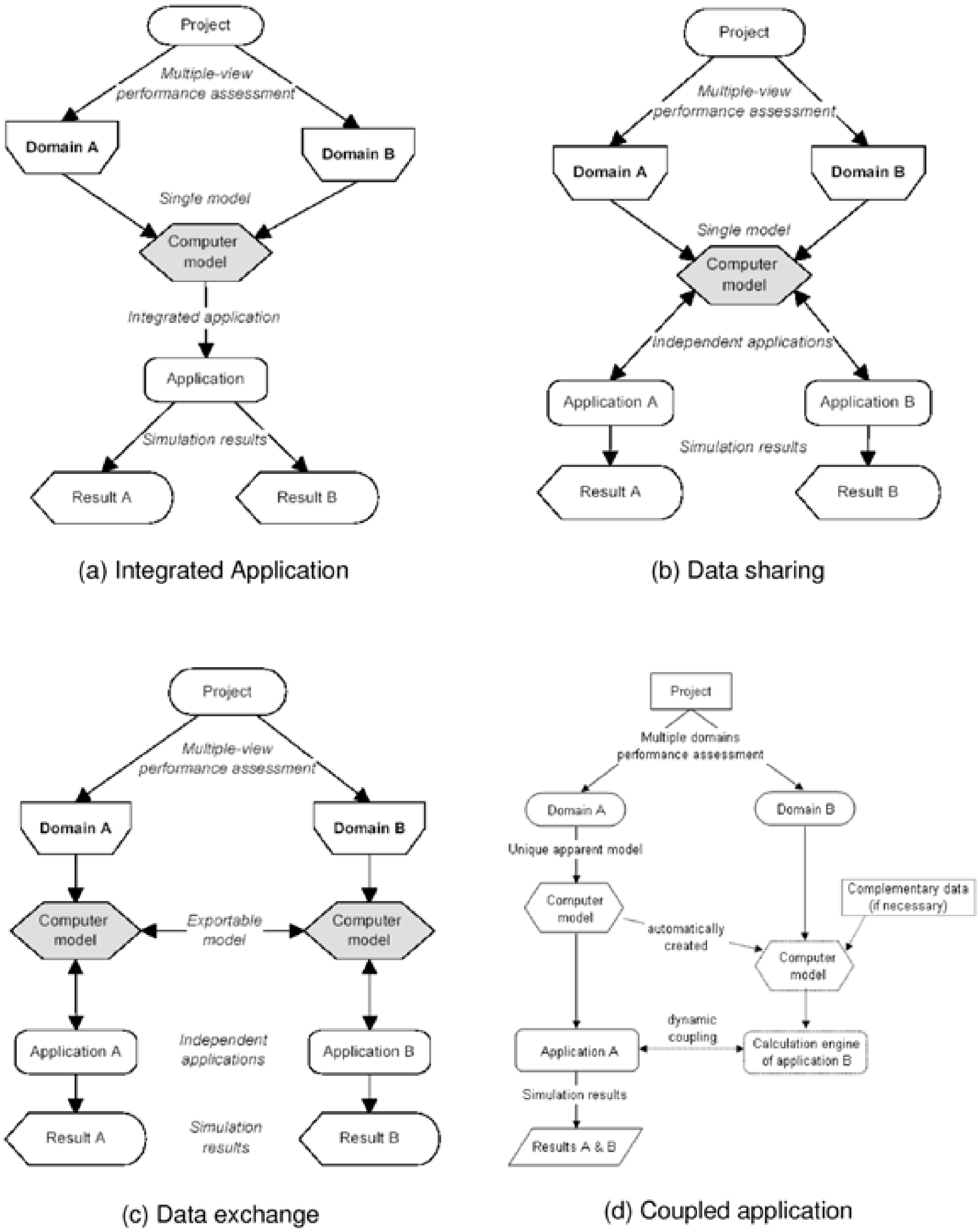


Figure 2.1 Different approaches to implement multi-domain simulation (Citherlet 2001)

2.2.2 Internal coupling vs. external coupling

From the user point of view, the main disadvantage of external coupling is the model development where the different programs involved in the coupled simulation require different models. Citherlet et al. 2001 indicated several disadvantages if we have to create more than one model for a single project: (1) it is time consuming, and (2) any modification in the project has to be translated between models.

In the current situation, this should be seen as a price for doing a coupled simulation. But many developments are currently on-going so that this should not be the case in the near future.

The data model interoperability as explained earlier can provide different models to different programs (although the programs are then running separately, as shown in Figure 2.1.b and Figure 2.1.c). For example, the BES can provide the geometry of the flow domain for the CFD simulation. It is not a big move to include this process into the external coupling method where the data sharing or exchange will play an important role in the "automatic model generation" (as depicted in Figure 2.1.d). The developments in interoperability (e.g. Karola et al. 2001) will eventually resolve the problem of multi-model problem in external coupling.

From the software development point of view, in my opinion, the external coupling promises many advantages over the internal coupling. The reason is summarized in the following paragraphs.

As has been summarized earlier in Chapter 1, the main problem of internal coupling is how to ensure the long-term maintenance of the software and associated libraries. Every development in any domains must be transferred in, and translated into new source code within the main program. There will be a significant number of code changes that have to go through a process of quality assurance of verification and validation.

On the other hand, the process of adopting developments in other domains is relatively easier with external coupling. Once the communication protocol between the programs has been established, future developments in any domains (e.g. new turbulence model or new wall function in CFD) can be easily made available to the coupled simulation using the already-developed communication protocol. Of course, that is with the assumption that the data structure for communication remains the same. Otherwise, the new data structure for communication has to be made. However, in general, there will be much less changes in the source code, and for this reason the associated cost of employing such method would be relatively much less expensive than the first scenario using the internal coupling.

Considering the two scenarios above, the internal coupling will have to go through a more difficult and longer than the external coupling. This will also cause the cost to increase dramatically.

2.2.3 Integration or coupling between CFD and BES

2.2.3.1 The need for integration

The coupling of BES and CFD simulation has been studied in various research in recent years, e.g. Negrao 1995, Srebric et al. 2000, Beausoleil-Morrison 2000, Zhai 2003. The two simulation programs, as any other simulation programs, have their own limitations. For example, the boundary conditions of CFD are usually assumed with limited consideration for the thermal storage effects of the wall, external conditions and interactions with building services systems. BES, on the other hand, calculates its energy prediction based on a well-mixed assumption so that the definition of the convective heat transfer coefficient (CHTC) cannot capture the dynamics of the flow near the surfaces.

The integration or coupling between the two programs is seen as an alternative to achieve better results because the two can provide boundary conditions to each other. For example, BES can provide internal surface temperatures of the walls to CFD, while CFD can provide more accurate CHTC values for BES.

The benefits of the coupled simulation have been discussed in the publications mentioned, and in general can be categorized into two advantages: (1) more accurate energy prediction due to more accurate CHTC value, and (2) ability to analyze the dynamical changes in airflow pattern in CFD due to the dynamic boundary conditions supplied by BES (e.g. Figure 5.29 and Figure 5.40). The above benefits will also be highlighted in the coupled simulations carried out in this study.

What has not been addressed in detail in the literature is the systematic assessment on when exactly the coupled simulation is needed. The coupled simulation is still associated with a high computing cost. BES-only simulation can run on any PC without special specification, and the simulation can be finished within minutes. A coupled BES-CFD simulation, on the other hand, will generally require more computing power, and the coupled simulation can take days to run.

It is imperative that we have a method to assess whether a coupled simulation can bring significant benefits to a particular problem before committing into a sophisticated method. This issue will be addressed in Chapter 3.

2.2.3.2 Integration strategy

There are three major categories as shown in general in Table 2.1 on how to implement the integration of the detailed building airflow (CFD) and the thermal domain. Each of the categories is described in the following paragraphs.

Table 2.1 Different strategies for coupling

Strategy	Description	Example
Hard coupling	Two or more sets of equations are combined and solved at the same time	o Conjugate heat transfer method in CFD
Loose coupling – internal coupling	Two or more sets of equations are solved separately, and exchange data during calculation	o CFD – BES coupling in ESP-r and EnergyPlus
Loose coupling – External coupling	Two or more set of equations solved separately, in different programs, and exchange data during calculation	o CFD – BES coupling in ESP-r and EnergyPlus o This work

The first method is to include the dynamics fabric model and (optional) radiation model into CFD to form what is called the conjugate heat transfer method (e. g. Chen et al. 1995 and Moser et al. 1995). It is based on including the thermal characteristics and processes in the walls into the model so that the boundary condition of the CFD models can be moved from the inside to the outside of the wall, and thus capturing the dynamics of the external conditions. This will result in a single set of equations to be solved in a single time step. All variables for both the fluid and the solid domains are up-dated simultaneously.

By moving the boundary condition from internal side of the surface to the external side, this method is the direct answer to the problem of setting up boundary condition for CFD without considering the use of BES (as a separate program). In fact, there is a tendency to avoid the use of BES for at least two reasons (Chen et al. 1995):

1. If the interior wall temperature is calculated by BES, then it needs the data (at least CHTC) from CFD. There would be an iteration process between the two to get an agreement on the values, and this iteration was seen as inconvenient.
2. The conduction heat transfer calculation in most BES packages assumes one–dimensional heat transfer which will introduce errors.

However, the application of the conjugate heat transfer method has several disadvantages:

1. The difference in stiffness of the fluid and the solid side of the model will lead to difficulties in obtaining a converged solution (Chen et al. 1995).
2. It is computationally expensive (Zhai et al. 2001). The computing time increases dramatically because of the difference in the time scale between fluid (few seconds) and solid (few hours) so that the calculation must be performed over a long time range to include the dynamics in the solid, but over a very small time step to account for the dynamics in the fluid.
3. Most probably, the code of the solvers must completely be rewritten.

There have been few developments on this method, including a new algorithm to stabilize the computation process. However, Zhai et al. 2001 concludes that this method is not practical for immediate use in the design context with current computer capabilities.

The second method of integration is to develop a CFD capability into a BES environment, e.g. Zhai et al. 2001, Beausoleil-Morrison et al. 2001 and Srebric et al. 2000. Different from earlier implementation where all sets of equation are (strongly) coupled and solved at the same time, this approach uses loose coupling where two separate sets of equations are solved separately but exchange data in a predefined way.

This method has some advantages that directly answer the restrictions of the previous approach:

1. There is no internal computational stiffness problem for either tool as the fluid and the solid side of the model is simulated/solved separately.
2. It is computationally less expensive since it does not solve the whole equations at the same time, and thus there are no two different time scales to deal with.
3. The solvers for the separate domains can be optimized individually to account for the characteristics of the respective domains.
4. It is possible to use a separate program without rewriting the code. This is a major advantage as we can immediately use codes that are available from each domain, which have been developed separately over the years, well proven and benchmarked.

Referring to discussions in earlier sections, the two methods above can be categorized as internal coupling where the domain expansion is addressed by including the new domain into existing software. Despite the successful implementation of both methods, in the long run it also brings all the limitations of internal coupling.

That is the reason that this thesis identified a ***third method*** to integrate CFD and BES: the external coupling. This thesis refers to <u>externally-coupled simulation</u> if:

1. Two or more programs are running simultaneously, <u>and</u>

2. There is a mechanism of external data exchange between the programs, either by a text file I/O or by more sophisticated inter-process communication (Yahiaoui et al. 2004).

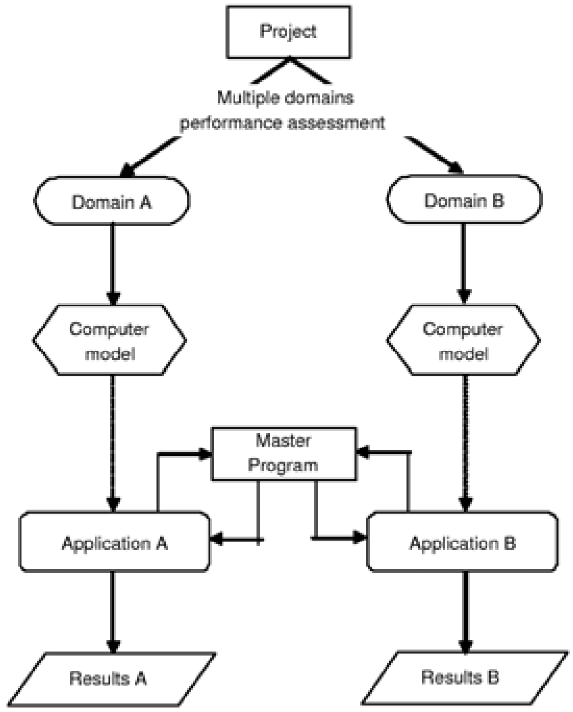


Figure 2.2 Coupled simulation (generalized) – the external coupling approach

This thesis proposes a more generalized view on coupled simulation (compared to what is proposed by Citherlet 2001 shown in Figure 2.1.d) as shown in Figure 2.2. A coupled simulation usually involves the following components:

1. Domain solvers
2. Geometry modeller and/or grid generator.
3. Master program which coordinates the coupling procedure, e.g.:
    - Frequency and point in the solution procedure where data is exchanged between the codes.
    - Definition of the variables that will be passed between the codes.
    - Method of time step control

Domain solvers are the main program to do the calculation. Each domain can have a separate geometry modeller. As mentioned earlier, the geometry can be manually developed, or it can be automatically generated by the other program.

A master program coordinates the coupling process, which can be assigned to any of the domain applications, so that one of them acts as the master and the other(s) are the clients, or it can be a separate program.

2.3 Methodology

The method employed by this thesis is the numerical simulation method. No experimental work was performed in this study. However, the numerical work is going through a quality assurance process. The following sections describe the important features of the methodology

2.3.1 Rapid prototyping

Rapid software prototyping is used in the implementation of external coupling. In this thesis, a software rapid prototype is defined as a working model that is developed from existing software to highlight a specific function with a minimum amount of effort.

The development can be summarized as follows:

1. Start from existing state-of-the-art program
2. Define requirements for the prototype
3. Implement the prototype with minimum changes on the code
4. Validate the prototype
5. Back to step 2 to refine or expand the requirements until the final prototype is built.

2.3.2 Start from existing state-of-the-art software

2.3.2.1 Building energy simulation (BES)

ESP-r (ESRU 2003) was selected as the BES package for this study. The ESP-r system has evolved to its present form over more then 3 decades. The initial prototype was developed by Prof. Joe Clarke (Clarke 1977). After that it has been under constant development until today.

ESP-r is capable of modelling the energy and fluid flows within combined building and plant systems when constrained to conform to control action. Different modules have been developed: project management, simulation, results recovery and display, database management and report writing.

ESP-r was selected because:

1. It is well validated through a large scale validation exercises (Lomas et al. 1994,PASSYS 1994)
2. It has its own BES – CFD coupling capability (Negrao 1995, Beausoleil-Morrison 2000), so that comparison between internal and external coupling can be made using the same BES package.

2.3.2.2 CFD

Most of the CFD codes used in practice are commercial programs where the source code is not available to the user. It is important that the external coupling method is developed with this scenario in mind. The users might not have the access to the source code of the CFD program they use.

The criteria for the CFD program is that the user should be able to define user-defined functions to a broad range of parameters and models that will override certain functions set by the source code. Many of the commercial programs meet these criteria. Fluent (Fluent 2003) is selected as the CFD program to be used in this study because of additional (more subjective) reasons of practicalities, e.g. Fluent is already available at the university.

However, this selection should not have any implications on the applicability of the external coupling method as the method should be applicable to any CFD (and BES) program.

2.3.3 Quality assurance

Any numerical simulation should always be accompanied by some confidence measure to ensure that the simulation result has enough credibility. One way to build the confidence is to do a validation study.

The validation study for this thesis will be conducted by using inter-model comparison (i.e. by comparing the result of external coupling with the results of earlier simulation) and by empirical validation (i.e. comparing the external coupling result with measurement data).

There was no measurement conducted for this study. For validation purpose, several high quality data were used. The measurement data were the results of large scale research projects that carried out the measurement to produce data for validation purpose. The projects, the measurement protocol and the measurement results have all been published in journals and conference papers.

The issue of quality assurance will be addressed in Chapter 5.

2.3.4 Tools and knowledge

Some prototypes were constructed using rapid software prototyping method. The prototypes act as proof-of-concept, and are not intended as the main result of this study.

The main deliverables of this study are the generalized requirements to implement external BES – CFD coupling. Together with the implementation example from this study (using ESP-r and Fluent), the requirements will allow anybody to replicate the implementation of external coupling using another BES and/or CFD package.

Chapter 3

Guidelines for (coupled) airflow simulation

With the advancement of technology, and with the widespread availability of simulation tools, we are forced to consider which simulation tool would be appropriate for a particular problem. The seemingly trivial decision is in reality not very easy to make. Very often this leads to the practice of using the most sophisticated tool available for every problem. The levels of resolution and complexity of simulations are directly related to the accuracy of the simulation and to the total cost of the simulation process. A simple tool may be cheaper, but there is a high risk of inaccuracy. An advanced tool could be more accurate, but it needs a huge amount of resource in terms of computing power, labour, and the advanced knowledge to perform the simulation and interpret the results. This chapter proposes a guideline for selecting a simulation tool for airflow prediction. Sensitivity analysis is selected as the tool for decision making. A case study is used to highlight the proposed method.

3.1 Introduction

The traditional method to design HVAC systems is the paper-and-pencil method using various engineering guidelines. This method has survived over the years, since the early days of engineering guidelines, as the trusted method.

However, there is a move towards simulation, which is rapidly becoming the most important engineering tool in integrated design of buildings and HVAC systems. There are at least three reasons for this (Slater and Cartmell 2003):

1. Newer and cost-effective construction techniques mean that the building form is departing more frequently from the stacked rectangular box. The data provided by the guidelines is less applicable to these new building forms.
2. There is a constant push for efficiency and refinement and to promote new design. The simplified equations in the guides are usually applied very generally. This means they have been formulated to be conservative to ensure that the designs that result from their use do not fail. Trying to refine this fail-safe design (to get more efficiency), without reducing the unknowns, is a direct path to failure. Simulation is seen as a way to reduce the unknowns.
3. The definition of successful HVAC is changing. The traditional “never over 24 °C” rule is often broken without complaints. The more advance rule with statistical measure – “temperature should not rise above 25 °C for more than 5% of the occupied hours” – means that the guides need additional tools as a supplement.

Simulations used to require supercomputer to run. But recent advances in hardware and software make simulation approaches widely available because it can now run on a personal computer. The flood of simulation tools poses the question of how to justify the selection of a certain approach or tool.

This chapter proposes a guideline to assess whether a coupled simulation is needed for a certain problem. The guideline can also be used to justify the selection of a simulation tool. Even though the guideline described in this chapter is focused on airflow simulation, it can be applied to other domains with a slight modification.

3.2 Problem statement

In airflow simulation, there are at least three approaches representing different resolution level:

1. Building energy balance models (BES) that basically rely on guessed or estimated values of airflow.
2. Zonal airflow network (AFN) models that are based on (macroscopic) zone mass balance and inter-zone flow-pressure relationships; typically for a whole building.
3. Computational fluid dynamics (CFD) that is based on energy, mass and momentum conservation in all (minuscule) cells that make up the flow domain; typically a single building zone.

Hensen et al. 1996 analyzed the capability and applicability of these approaches in the context of a displacement ventilation system. The main conclusions from this study are:

1. Each approach has its own merits and drawbacks. An environmental engineer typically needs each approach but at different times during the design process.

2. A higher resolution (and more complex) approach does not necessarily provide answers to all the design questions that may be answered by a lower resolution (less complex) approach.

Table 3.1 summarizes the findings of Hensen et al. 1996.

Table 3.1 Summary of prediction potential (--=none, ++=very good) for airflow simulation resolution levels in case of displacement ventilation (Hensen et al. 1996)

Aspect	BES	AFN	CFD
Cooling electricity	--	++	--
Fan capacity	++	++	--
Whole body thermal comfort	+	++	+
Local discomfort, gradient	--	+	++
Local discomfort, turbulence intensity	--	--	++
Ventilation efficiency	--	0	++
Contaminant distribution	-	-	++
Whole building integration	++	++	--
Integration over time	++	++	--

These are important findings in the middle of the abundance of simulation tools. When the various tools become available, it should be realized that a high resolution (and more complex) approach requires an enormous amount of resources in terms of computing capacity, manpower and time. On the other hand, lower resolution (and less complex) approaches might not reliably solve a particular problem. How to select the appropriate approach to solve the problem at hand remains the challenge.

There is always a temptation to use the most sophisticated method to simulate every design option. The sophistication would hardly fail to impress any client. However, the cost of such sophistication should always be justified, otherwise the client will hesitate to use the same method in the future. This could affect the positive growth in the widespread use of simulation in building design. In this perspective, there is a need for a guideline to decide which simulation tool/ approach is appropriate for a certain problem.

Slater and Cartmell 2003 developed what is called “***early assessment design strategies***” (Figure 3.1). From the early design brief, the required complexity of the modelling can be assessed. Starting from the design standard, a building design can be assessed whether it falls safely within the Building Regulations criteria, or in the borderline area where compliance might fail, or whether it is a new innovative design altogether. Based on this initial assessment, and with the proposed HVAC strategy, several decision points in Figure 3.1 would help the engineer to decide which level of complexity should be used for simulation.

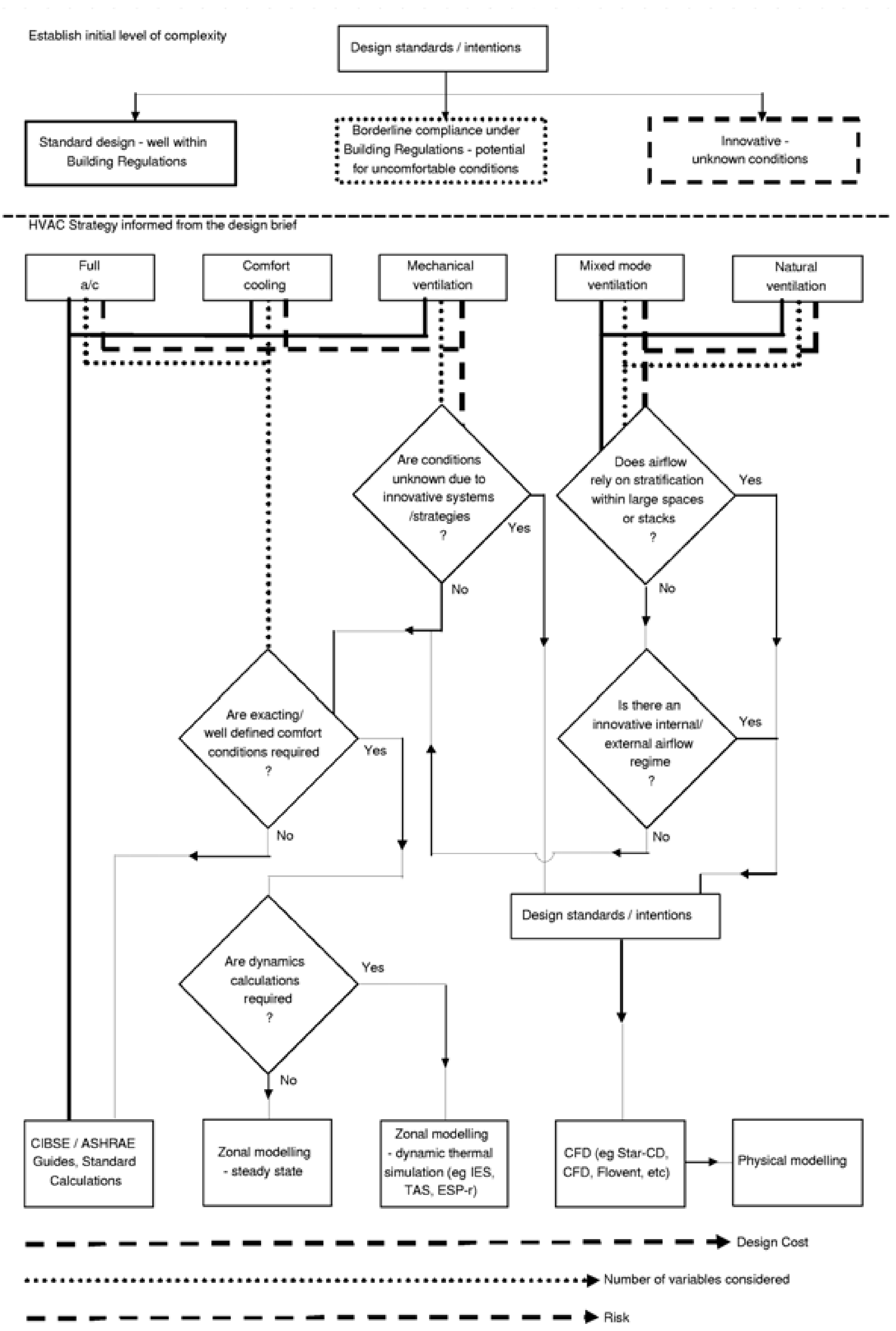


Figure 3.1 Early assessment design strategies

3.3 The guideline

The proposed guideline is developed based on the findings of the previous research described earlier. Early assessment design strategies as proposed by Slater and Cartmell 2003 can be used for initial assessment. However, I identified the need to go further because of the following reasons:

1. As Hensen et al. 1996 pointed out, we need to use different levels of complexity and resolution at different stages of a building design.
2. Coupled simulation (between energy simulation and CFD, for example) is now a viable option, which is not addressed in Figure 3.1.

Figure 3.2 shows the proposed Coupling Procedure Decision Methodology (CPDM). Because of the high cost of coupled simulation, CPDM was proposed to identify the need for coupled simulation. However, the CPDM can also be applied more generally to assess the need for a certain level of complexity and resolution for simulation.

The main ideas behind the CPDM are:

1. A simulation should be consistent with its objective (problem-led), i.e. the designer should not be tool-led. This means that a simulation tool should not be selected simply because it is the only one available, or because it is the most sophisticated tool. The simulation tool should be selected because the problem requires the tool.
2. there should be a problem-led rationale to progress from one level of resolution and complexity to the next,
3. the selection of good design option (among many design options) should be made at the lowest possible resolution and complexity, so that there would be less design option to be simulated at higher resolution level.

In the vertical axis (Figure 3.2) there are layers of different resolution of building simulation. There are four layers representing the increased level of resolution, i.e. energy simulation, airflow network simulation, and two levels of CFD simulation. Each of the resolution layers is separated by one or more decision layers. The horizontal axis shows the different levels of complexity of building simulation.

The first step is to select the minimum resolution based on the design question at hand. For example:

- If energy consumption is needed, than BES would be sufficient.
- If the temperature gradient is needed, than at least an AFN is required.
- If local mean age of air is in question, than CFD is necessary.

A second step is to check whether the above minimum resolution is sufficiently accurate for the design question at hand. For example:

- A load analysis based on BES may be over-sensitive to the convective heat transfer coefficient (CHTC) values, thus requiring CFD to predict more accurate CHTC values.
- A load analysis may be over-sensitive to the ‘guestimated’ values of infiltration or inter-zonal ventilation, thus requiring AFN to predict more accurate airflow rates.

How to actually make these decisions is to a large extend still vague as denoted by the question marks in Figure 3.2. In practice the decisions are often made implicitly and depend very much on the skills and experience of a design engineer. With CPDM this implicit process is made explicit and structured. Performance indicators and sensitivity analysis are used for this purpose.

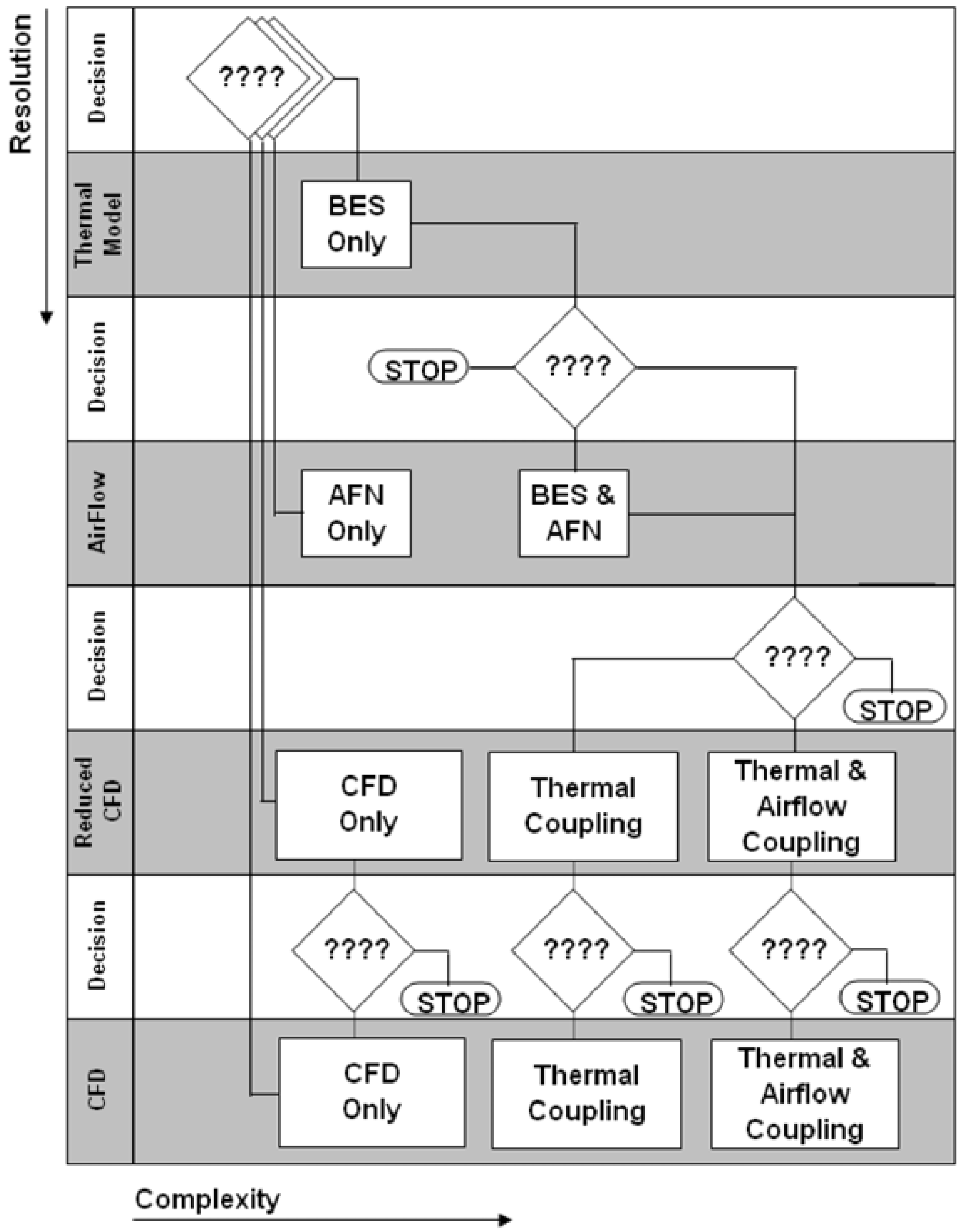


Figure 3.2 Coupling Procedure Decision Methodology

3.3.1 Performance Indicators

CPDM uses performance indicators as the base to make decisions on which simulation tool/approach is the appropriate tool for the design question at hand. This is a step further from what was proposed by from Slater and Cartmell 2003 who used the early design brief as the base for the decision making. Table 1 shows a typical list of performance indicators (PI) that are of interest for an environmental engineer. The indicators basically fall into three categories, i.e.

energy related, load related and comfort related performance indicators. Each of these categories will be used for different kinds of decisions in the building design process.

Table 3.2 Performance indicators and minimum required modeling resolution in terms of simulation approach

Performance Indicators	Approach
Energy Related	
a. Heating energy demand	**BES**
b. Cooling energy demand	**BES**
c. Fan electricity	**BES**
d. Gas consumption	**BES**
e. Primary energy	**BES**
Load Related	
f. Max heating load	**BES**
g. Max cooling load	**BES**
Comfort Related	
h. PPD	**BES**
i. Max temperature in the zone	**BES**
j. Min temperature in the zone	**BES**
k. Over heating period	**BES**
l. Local discomfort, temp gradient	**AFN**
m. Local discomfort, turbulence intensity	**CFD**
n. Contaminant distribution	**AFN**
o. Ventilation efficiency	**AFN**
p. Local mean age of air	**CFD**

In every category, there is more than one indicator. Some indicators can be obtained directly from simulation results. Others need additional treatments, either manual “paper-and-pencil” calculation or additional simulation. There is no attempt to put a weight on the indicators to highlight their significance, as each building design could have different weight for the same performance indicators.

With regard to the CPDM, these indicators are used as the basis for the selection of the most appropriate approach to simulate the problem at hand. Table 3.2 also shows the minimum resolution required to calculate a performance indicator. As we can see, only a few indicators require an immediate jump to the AFN or CFD approach. It should be noted that this list is case dependent. In case of naturally ventilated double skin façades, for example, load and energy calculations will require an airflow network approach.

3.3.2 Sensitivity analysis

Sensitivity analysis is the systemic investigation of the reaction of the simulation response to either extreme values of the model’s quantitative factors or to drastic changes in the model’s qualitative factors (Kleijnen 1997). This analysis has been used in many fields of engineering as a what-if analysis, and one example of the use of this method in building simulation is described by Lomas and Eppel 1992.

The main use of sensitivity analysis is to investigate the impact of a certain change in one (or more) input parameters to the output. Depending on the particular problem, the end result is usually to identify which input parameter has the most important impact on the output. It is an unavoidable step in model verification and/or validation. However, Furbringer and Roulet 1999 suggested that sensitivity should also be used in performing simulations.

In the CPDM, the sensitivity analysis is used for a slightly different purpose, as we are not trying to identify which input is important, but we rather try to identify the effect of changes in one input to a number of outputs. Which input is used in this study is selected from the result of previous research in this area.

From previous studies, e.g. (Beausoleil-Morrison 2000, Hensen 1991, Negrao 1995), there are two main inputs that should be tested for sensitivity analysis for the decision to progress to higher resolution level:

1. Airflow parameters assumption, especially the infiltration rate, for the decision to use AFN-coupled simulation. (Further sensitivity analysis on airflow parameters is denoted as SA_{af})
2. Convective heat transfer coefficient, for the decision to use CFD. (Further sensitivity analysis on CHTC is denoted as SA_{hc})

For SA_{af}, the possible minimum and maximum values of airflow parameters (e.g. infiltration value) are estimated. For SA_{hc}, the possible minimum and maximum values of CHTC are estimated. These minimum and maximum values of airflow parameters and CHTC will then be used in simulating the problem.

In the usual use of sensitivity analysis where there are many inputs and one single output, the effect of each input can be easily compared and there is a single term (or parameter) to quantify the effect of each input parameter on the output. However, with the use of sensitivity analysis for the CPDM, for every performance indicator there are five values, one for the base case, SA_{af-min}, SA_{af-max}, SA_{hc-min}, SA_{hc-max}. It is not as straight forward to formulate a decision rule based on these five values.

3.3.3 Decision rules

The five values mentioned above can be presented as a bar chart (as in Figure 3.3) with three output conditions of the performance indicators, each of them corresponding to the minimum value, maximum value and base condition value of the input. The minimum and maximum values form an error band around the base case. Based on the error band and how different performance indicators are considered, there are three levels of decision rule that can be formulated.

In level one, a single value of error band is applied to all performance indicators. The value (let say, error band of 20%) is used to decide whether the problem is sensitive or not. If the error band shows more than 20% deviation from base case value, then the problem is considered as sensitive. On the other hand, if the error band is less then 20%, the problem is considered not sensitive.

The level one decision rule is very simple, as it only looks into the deviation from the base case. Furthermore, it uses a single error band value for all performance indicators. This is an obvious limitation, as the error band means differently for different performance indicators. For example, 20% deviation in air temperature has less significant meaning compared to 20% deviation in energy demand.

In level two, the error band value is compared to a reference value (which is based on a guideline or standard). Figure 3.3 shows two scenarios on how the level two decision rules operate. Each of the performance indicators would have a “reference value” that can be found from building codes, standards, or guidelines, or even from “good-practices” experience. The reference value can be a maximum value, minimum value, or a range of acceptable values.

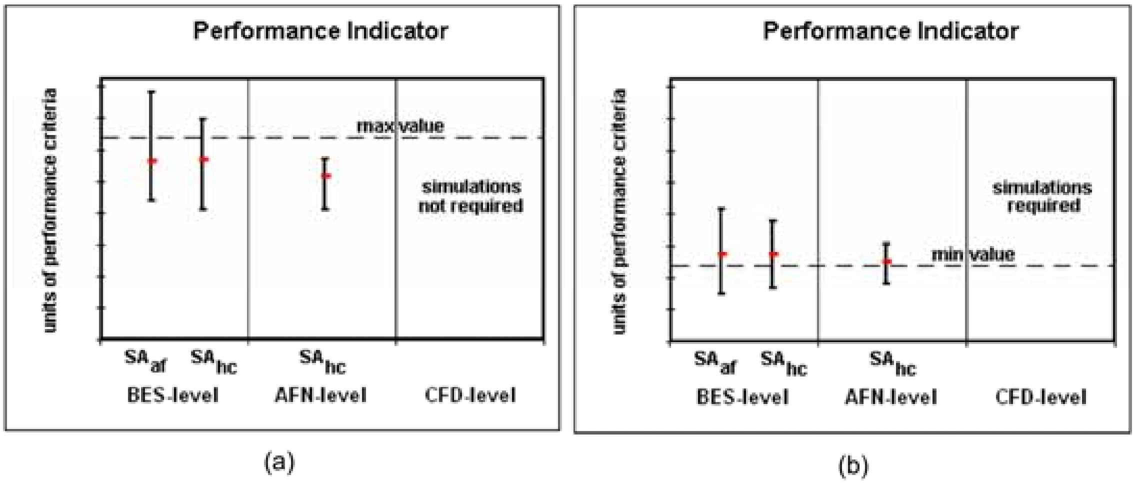


Figure 3.3 Assessment of the validity of the level of resolution through sensitivity analysis

In Figure 3.3 (a), the output value could be more than the maximum reference value, based on the result of BES-only simulation, and the SA_{af} result indicates that an AFN-coupled simulation is necessary. However, in the AFN-level, the SA_{hc} result indicates that all predicted values are below the maximum reference value, thus no subsequent CFD calculation is required.

In Figure 3.3 (b), the output value could be less than the minimum target value, based on the result of BES-only simulation, and the SA_{af} result indicates that an AFN-coupled simulation is necessary. In the AFN-level, the SA_{hc} result indicates that there is a possibility that the output value is below the minimum target value, thus in this case a CFD calculation is required.

The level two decision rule is slightly more complex than level one. It allows different performance indicators to be assessed using different reference values. However the performance indicators are assessed separately. Which performance indicators are considered as important, depends on the engineers experience when the results are analyzed.

In level three, the decision rule includes aggregation of performance indicators. This rule includes the rules in both levels one and two, with additional rule on how to aggregate the various performance indicators. The aggregation is actually a set of weighting factors with which the engineers can put the degree of importance of a certain performance indicators in the design problem. The set of weighting factors is, of course, case dependent. Different case will have different set of weighting factors.

This complex rule is needed in the view of automatic decision making in the design process. The simulation will decide, based on the aggregated values of performance indicators, whether the design problem needs a certain resolution or a certain complexity.

This thesis does not develop the rules on levels two and three. A level one decision rule is used in the case study below to show the applicability and the usefulness of the CPDM.

3.4 CASE STUDY

3.4.1 Model description

The following case study is presented to highlight the application of the CPDM. This case study concerns an open-plan office space in a new faculty building (Figure 3.4) at the Technishce Universiteit Eindhoven. The computer model comprises a 6 m wide and 12.5 m deep section of a 5.4 m high office space. The one external wall is a double-glazed structure, facing south. All other walls are assumed to be adiabatic. The section is assumed to have 10 occupants during office hours, with lights and equipments this leads to 35 W/m^2 internal gains. There is an all-air heating and cooling system serving the area.

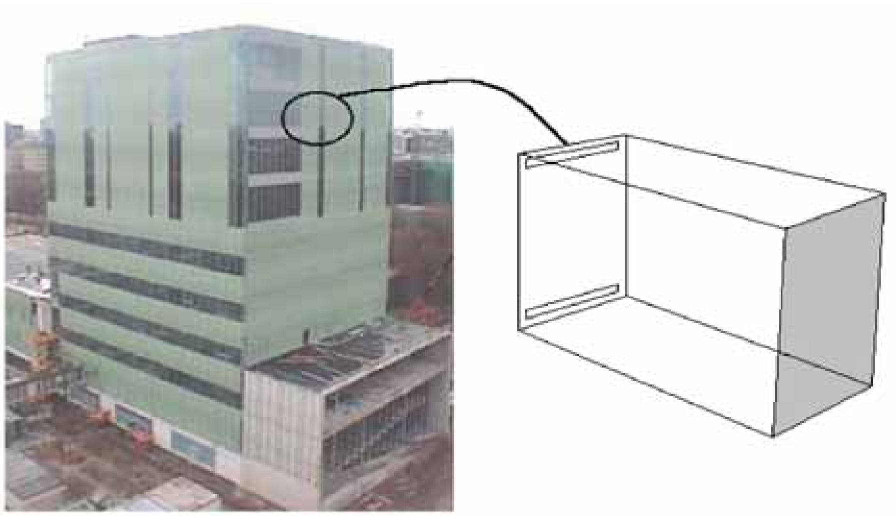


Figure 3.4 The building and the model

Given the large glazing area, the environmental designer would like to predict the energy consumption, heating and cooling loads, and the most important is the likelihood of thermal comfort complaints, which may arise both in summer and winter conditions. Thermal comfort complaints might result from thermal radiation asymmetry and/ or from a cold down draft due to the large glazed area. Several design options are considered for comparison. Table 3.3 shows the different design options for this case study.

3.4.2 Case study methodology

On the first layer in Figure 3.2, BES-only simulation, typical office conditions are used as simulation parameters for the "base condition". After that, the cases are subjected to two sensitivity analyses:

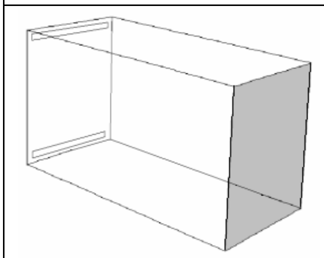
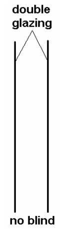
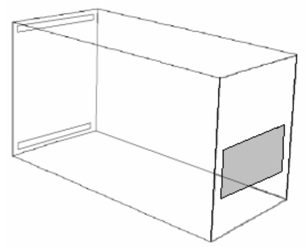
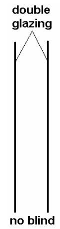
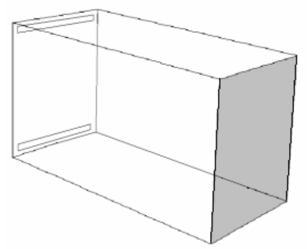
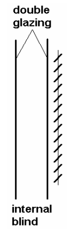
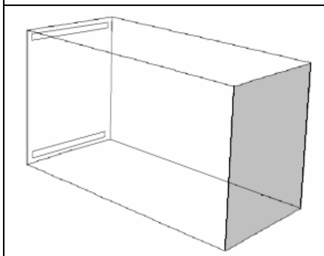
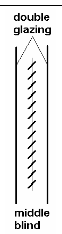
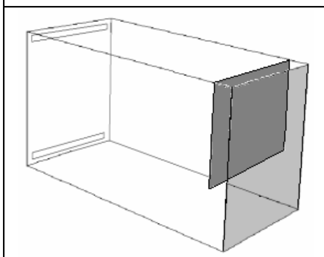
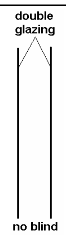
1. Airflow parameter.

   In the base condition, the infiltration rate is assumed to be 0.3 ACH. In reality, it could be somewhere between 0.05 - 0.5 ACH. These two values would be the minimum and maximum value for the sensitivity analysis.

2. Convective heat transfer coefficient.

   In the base condition, the simulation uses the Alamdari-Hammond method for the specification of the convective heat transfer coefficient. However, the flow in the room could be another type of flow, which has coefficients ranging from 1 – 6 W/m^2K. These two values are taken as the minimum and maximum value for the sensitivity analysis.

Table 3.3 Different design options for this case study

Isometric view	Glazing	Remarks
		Conf. 1 = Base case
		Conf. 2 is the same as the Conf. 1, but the glazing area is reduced to 2mX4m.
		Conf. 3 is the same as Conf. 1, with additional blinds in the internal part of the room
		Conf. 4 is the same as Conf. 1, with additional blinds in the middle between the two glazing.
		Conf. 5 is the same as Conf. 1, with additional curtain 0.5m from the wall, down to 2m above the floor.

ESP-r is used as the software for the simulation. The air conditioning strategy for all simulations is to maintain the PPD level to be less than 10% during office hours. This is achieved by setting the operative temperature at 23 °C and 26 °C for winter and summer respectively, i.e. the temperature in the middle of the zone. By maintaining the PPD level, the whole simulations want to show the energy consequences of maintaining a high level of comfort standard to the space. It should be noted however, that the PPD “controller” as used in this simulation is not a normal parameter, but it is an idealized scenario that is interesting to be studied due to the presence of a large window area.

The results of the sensitivity analyses are used to determine whether the simulation on a higher resolution level is needed or not, and, if this is required, which configurations are tested.

On the second layer, AFN, the airflow network model is used to represent some significant airflow in the buildings. Figure 3.5 and Figure 3.6 present the airflow network configurations that have been used for the AFN-coupled simulation. The fans supply fresh air for 10 people (i.e. 10 lps per person or 0.1 m^3/s). The infiltration through the exposed wall is now calculated by the network model and not assumed as in the BES-only simulation. This is represented by the line between "south" and "zone" nodes. For Configuration 5, as in Figure 6, there is one additional node in the gap between the glazed wall and the curtain. The air in the gap exhausts at 0.01 m^3/s when the temperature reaches 27 °C.

The coupled BES-AFN simulation is indicated as the "base condition" on this level. All selected configurations were subject to a sensitivity analysis for the convective heat transfer coefficient. In the base condition again the Alamdari-Hammond method for the specification of convective heat transfer coefficient is applied. Again, the result of the sensitivity analysis is used to determine whether a simulation on a higher resolution level is needed or not, and if it is required, which configurations should be tested.

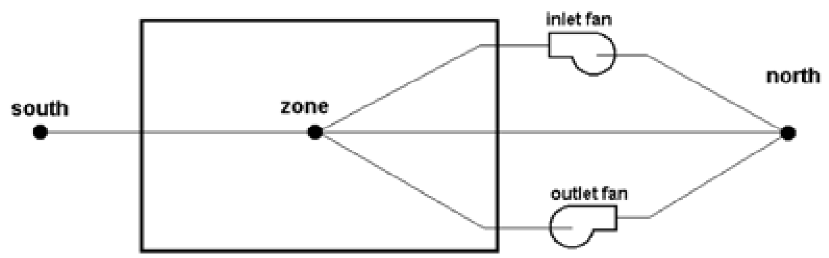


Figure 3.5 Airflow network for Configurations 1 to 4

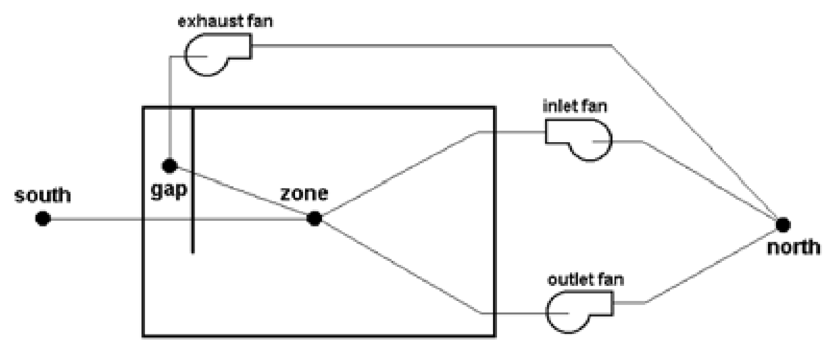


Figure 3.6 Airflow network for Configuration 5

On the third layer, CFD, the simulation is focused on the distribution of the airflow parameters in the room. The result from a previous simulation (i.e. wall temperature and heat extraction rate) is supplied as boundary condition for the CFD calculation. The energy calculation is repeated using the convective heat transfer coefficient value supplied from the CFD calculation result.

Table 3.2 indicates the minimum required resolution for each performance indicator. It is obvious that the simulations on higher resolution level should have less configuration (or cases) to be tested. The decision on which configurations are to be simulated at higher resolution cannot be made in advance, this is the result of the performance assessment.

3.4.3 Results for BES-only simulation

In Table 3.4 and Table 3.5 the results are presented for the investigated performance indicators. Here "af" indicates the sensitivity for the airflow parameter and "hc" for the convective heat transfer coefficient. The results of the sensitivity analysis are presented in terms of the maximum deviation from the base condition. This deviation is expressed in a percentage value (S_{af}. and S_{hc}).

All cases in this example have been weighted similarly. However, a 20% deviation in the maximum zone temperature will have a less important meaning than a 15% deviation in primary energy. Therefore, in reality a design team will apply weighting factors to the individual cases and make their decision based on these weighing factors and the sensitivity results.

The PPD level in the room during office hours in a typical week in winter and summer is shown. As can be seen, the PPD values are well below 10% as expected, as this was the criteria for the simulation. The PPD presented here is only from one location, i.e. near the glazed wall, as this is the most critical location where discomfort complaints are expected. The value of PPD in this location should of course be different from the center of the zone where the operative temperature is controlled.

However, in the result, the PPD values considered for decision making (in CPDM) are from other location, i.e. in occupied zone (1m from the floor, three locations along long axis of the room).

For heating energy demand, Configuration 3 shows the highest energy demand, while Configuration 2 is the lowest. Nevertheless, all configurations show a high sensitivity to the airflow parameters. The sensitivity to the convective heat transfer coefficient is lower.

A similar discussion can be made for the cooling energy demand, the maximum heating load, and the maximum cooling load. The gas consumption, fan electricity consumption and the primary energy consumption can be derived from the above results and by applying some assumptions on, e.g. the boiler and fan efficiency. Finally, the maximum and minimum zone temperature and the overheating period are indicated.

3.5 Discussion

3.5.1 The use of the CPDM to determine the correct resolution level

The above presented sensitivity analysis is used in the CPDM to select the appropriate level of resolution. The maximum deviation from the base condition indicates the level of sensitivity of each performance indicator to the airflow parameter and the convection coefficient. In this example an arbitrary value of 20% is selected as the limit of sensitivity below which the performance indicator is not considered sensitive to the airflow parameter (S_{af}) or the convective heat transfer coefficient (S_{hc}). This is shown in Table 3.6. Here the sensitivity higher than 20% is shaded, indicating the need for that specific case to be simulated at a higher resolution level.

Table 3.4 Results of sensitivity analysis for different configurations (BES-only) (continued)

	Configurations	Base Condition	af		hc		S_{af}	S_{hc}
			min	max	min	max		
Heating energy demand	Configuration 1	4891	3057	6383	4510	5866	38%	20%
	Configuration 2	3570	1415	5346	3462	3920	60%	10%
	Configuration 3	6883	4586	8664	6443	8012	33%	16%
	Configuration 4	4798	2638	6529	4641	5336	45%	11%
	Configuration 5	4207	2212	5833	4008	4791	47%	14%
Cooling energy demand	Configuration 1	3734	4803	3148	3583	3612	29%	4%
	Configuration 2	1462	2572	971	1476	1361	76%	7%
	Configuration 3	719	1134	529	676	737	58%	6%
	Configuration 4	1448	2251	1053	1388	1455	55%	4%
	Configuration 5	2168	3209	1628	2175	2016	48%	7%
Max heating load	Configuration 1	17	14	19	12	28	17%	66%
	Configuration 2	14	11	17	11	23	25%	61%
	Configuration 3	18	15	20	13	29	16%	64%
	Configuration 4	16	13	18	12	26	20%	62%
	Configuration 5	15	12	18	11	24	21%	57%
Max cooling load	Configuration 1	14	14	13	10	15	5%	25%
	Configuration 2	6	6	5	5	6	13%	11%
	Configuration 3	7	7	6	5	8	7%	25%
	Configuration 4	7	8	7	6	8	7%	21%
	Configuration 5	8	8	7	7	8	10%	13%
Gas consumption	Configuration 1	611	382	798	564	733	38%	20%
	Configuration 2	446	177	668	433	490	60%	10%
	Configuration 3	860	573	1083	805	1002	33%	16%
	Configuration 4	600	330	816	580	667	45%	11%
	Configuration 5	526	276	729	501	599	47%	14%
Fan energy consumption	Configuration 1	3714	3714	3714	3714	3714	0%	0%
	Configuration 2	3714	3714	3714	3714	3714	0%	0%
	Configuration 3	3714	3714	3714	3714	3714	0%	0%
	Configuration 4	3714	3714	3714	3714	3714	0%	0%
	Configuration 5	3714	3714	3714	3714	3714	0%	0%

3.5.2 The use of CPDM to select a better design option

Before the next higher resolution level is addressed a selection procedure should be performed. The selection will normally be made in consultation with the design team. In the example, the simulation principle is based on maintaining the PPD level. The important parameters for the selection process are therefore the energy related performance indicators, most importantly the primary energy.

From the primary energy point of view, Configuration 1 has the highest primary energy value and therefore is not preferred. If architectural considerations are less important, and hence the construction can be changed, Configuration 2 is the best design option. However, if architectural considerations are the main restriction and cannot be changed, then Configuration 4 and Configuration 5 should be selected for simulation at a higher resolution level. Although it is not presented here, the same decision procedure can be made on the other decision points (the question marks in Figure 3.2).

Table 3.5 Results of sensitivity analysis for different configurations (BES-only) (continued)

	Configurations	Base Condition	af		hc		S_{af}	S_{hc}
			min	max	min	max		
Primary energy	Configuration 1	12339	11573	13245	11806	13193	7%	7%
	Configuration 2	8745	7701	10031	8651	8995	15%	3%
	Configuration 3	11316	9434	12907	10834	12463	17%	10%
	Configuration 4	9959	8603	11295	9743	10506	14%	5%
	Configuration 5	10089	9135	11175	9897	10521	11%	4%
PPD winter	Configuration 1	8	8	8	8	8	0%	6%
	Configuration 2	8	8	8	8	7	1%	4%
	Configuration 3	8	8	8	8	8	0%	6%
	Configuration 4	8	8	8	8	7	0%	5%
	Configuration 5	7	7	7	7	7	1%	4%
PPD summer	Configuration 1	6	6	6	6	6	1%	8%
	Configuration 2	6	6	6	6	6	0%	3%
	Configuration 3	7	7	6	7	6	2%	3%
	Configuration 4	7	7	7	7	7	0%	5%
	Configuration 5	6	6	6	6	6	0%	2%
Max zone temperature	Configuration 1	36	39	36	37	35	9%	4%
	Configuration 2	33	31	34	35	30	6%	8%
	Configuration 3	36	34	36	37	31	4%	11%
	Configuration 4	34	33	35	37	31	3%	9%
	Configuration 5	33	33	34	35	31	3%	7%
Min zone temperature	Configuration 1	9	11	8	9	10	22%	9%
	Configuration 2	11	14	10	11	13	24%	13%
	Configuration 3	9	11	8	8	10	22%	10%
	Configuration 4	10	12	9	10	11	23%	12%
	Configuration 5	11	13	9	10	12	21%	11%
Overheating	Configuration 1	522	1061	359	1162	296	103%	123%
	Configuration 2	80	621	56	238	36	681%	199%
	Configuration 3	169	155	207	495	25	22%	193%
	Configuration 4	150	384	157	338	64	157%	126%
	Configuration 5	262	983	150	599	118	275%	129%

Table 3.6 Results of sensitivity analysis with BES-only simulation for all configurations

Performance Indicators	Configuration 1			Configuration 2			Configuration 3		
	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}
Heating energy demand	4891	38%	20%	3570	60%	10%	6883	33%	16%
Cooling energy demand	3734	29%	4%	1462	76%	7%	719	58%	6%
Max heating load	17	17%	66%	14	25%	61%	18	16%	64%
Max cooling load	14	5%	25%	6	13%	11%	7	7%	25%
Gas consumption	611	38%	20%	446	60%	10%	860	33%	16%
Fan energy consumption	3714	0%	0%	3714	0%	0%	3714	0%	0%
Primary energy	12339	7%	7%	8745	15%	3%	11316	17%	10%
PPD winter	8	0%	6%	8	1%	4%	8	0%	6%
PPD summer	6	1%	8%	6	0%	3%	7	2%	3%
Max zone temperature	36	9%	4%	33	6%	8%	36	4%	11%
Min zone temperature	9	22%	9%	11	24%	13%	9	22%	10%
Overheating	522	103%	123%	80	681%	199%	169	22%	193%

(a) (b) (c)

Performance Indicators	Configuration 4			Configuration 5		
	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}
Heating energy demand	4798	45%	11%	4207	47%	14%
Cooling energy demand	1448	55%	4%	2168	48%	7%
Max heating load	16	20%	62%	15	21%	57%
Max cooling load	7	7%	21%	8	10%	13%
Gas consumption	600	45%	11%	526	47%	14%
Fan energy consumption	3714	0%	0%	3714	0%	0%
Primary energy	9959	14%	5%	10089	11%	4%
PPD winter	8	0%	5%	7	1%	4%
PPD summer	7	0%	5%	6	0%	2%
Max zone temperature	34	3%	9%	33	3%	7%
Min zone temperature	10	23%	12%	11	21%	11%
Overheating	150	157%	126%	262	275%	129%

(d) (e)

3.6 Results of BES – AFN coupled simulation

As in BES-only simulations, again the PPD is used as the target parameter that is to be maintained throughout the simulations. The target PPD value is 10%. In Table 3.5 results for the coupled simulation, including the sensitivity study are shown, similar to results presented in Table 3.7. The sensitivity in this case is restricted to the convective heat transfer coefficient, as the airflow parameter is dealt with in the AFN.

Table 3.7 Results of sensitivity analysis for different configurations (AFN-coupled)

Configuration	Heating energy demand		Cooling energy demand		Fan energy consumption	
	BaseValue	S_{hc}	BaseValue	S_{hc}	BaseValue	S_{hc}
Configuration 1	1029	83%	7055	3%	3714	0%
Configuration 4	3128	14%	2539	3%	3714	0%
Configuration 5	573	64%	5369	4%	3714	0%
	(a)		(b)		(c)	

Configuration	Gas consumption		Primary energy		Max heating load	
	BaseValue	S_{hc}	BaseValue	S_{hc}	BaseValue	S_{hc}
Configuration 1	129	83%	11798	7%	12	89%
Configuration 4	391	14%	9381	5%	14	60%
Configuration 5	72	64%	9656	2%	11	82%
	(d)		(e)		(f)	

Configuration	Max cooling load		PPD winter		PPD summer	
	BaseValue	S_{hc}	BaseValue	S_{hc}	BaseValue	S_{hc}
Configuration 1	14	30%	6	6%	6	10%
Configuration 4	8	21%	6	3%	7	4%
Configuration 5	8	18%	8	4%	6	1%
	(g)		(h)		(i)	

Configuration	Max zone temperature		Min zone temperature		Overheating	
	BaseValue	S_{hc}	BaseValue	S_{hc}	BaseValue	S_{hc}
Configuration 1	40	7%	12	6%	1966	65%
Configuration 4	35	11%	13	9%	841	97%
Configuration 5	34	7%	14	9%	1707	68%
	(j)		(k)		(l)	

Again, at this point in the design process, there are two decisions that should be made, whether a CFD-coupled simulation is needed, and if yes, which configuration(s) should be selected for further simulation. Therefore in Table 3.8, the results of the sensitivity analysis with the AFN-coupled simulations are compared to the results for the BES-only simulations. The results are shown for Configurations 1, 4 and 5 respectively.

In Table 3.7 significant differences can be found between the calculated individual performance indicators for the two approaches. Differences up to a factor of five and higher are calculated, especially for the energy related performances.

Some differences are expected as in this case an explicit definition of the infiltration rate through the glazed wall is applied. However, the large difference with the values of the performance indicators for the base condition suggests that there is a large difference in the infiltration value between the two simulation approaches.

Table 3.8 therefore shows the typical infiltration rates through the glazed wall that is calculated with the BES-AFN coupled simulation. When the fan is on (during office hours), the infiltration value is negative, indicating an outflow from the zone. The infiltration rate remains relatively constant. When the fan is off, the values fluctuate and the flow direction alternates. The table indicates the average values of this fluctuating flow. The values are much lower than the 0.3 ACH that was assumed in the BES-only simulation. The values are even less than the minimum value for sensitivity analysis, which was set at 0.05 ACH.

Table 3.8 Results of sensitivity analysis with AFN-coupled simulation for all configurations

	Performance Indicators	BaseValue		S_{hc}	
		BES-only	AFN-coupled	BES-only	AFN-coupled
Configuration 1	Heating energy demand	4891	1029	20%	83%
	Cooling energy demand	3734	7055	4%	3%
	Max heating load	17	12	66%	89%
	Max cooling load	14	14	25%	30%
	Gas consumption	611	129	20%	83%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	12339	11798	7%	7%
	PPD winter	8	6	6%	6%
	PPD summer	6	6	8%	10%
	Average zone temp - winter	25	27	5%	5%
	Average zone temp - summer	23	22	9%	12%
	Max zone temperature	36	40	4%	7%
	Min zone temperature	9	12	9%	6%
	Overheating	522	1966	123%	65%
Configuration 4	Heating energy demand	4798	3128	11%	14%
	Cooling energy demand	1448	2539	4%	3%
	Max heating load	16	14	62%	60%
	Max cooling load	7	8	21%	21%
	Gas consumption	600	391	11%	14%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	9959	9381	5%	5%
	PPD winter	8	6	5%	3%
	PPD summer	7	7	5%	4%
	Average zone temp - winter	25	26	5%	4%
	Average zone temp - summer	24	24	4%	5%
	Max zone temperature	34	35	9%	11%
	Min zone temperature	10	13	12%	9%
	Overheating	150	841	126%	97%
Configuration 5	Heating energy demand	4207	573	14%	64%
	Cooling energy demand	2168	5369	7%	4%
	Max heating load	15	11	57%	82%
	Max cooling load	8	8	13%	18%
	Gas consumption	526	72	14%	64%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	10089	9656	4%	2%
	PPD winter	7	8	4%	4%
	PPD summer	6	6	2%	1%
	Average zone temp – winter	25	27	4%	4%
	Average zone temp – summer	24	23	6%	7%
	Max zone temperature	33	34	7%	7%
	Min zone temperature	11	14	11%	9%
	Overheating	262	1707	129%	68%

This (large) difference between the results of BES-only and AFN-coupled simulation should be seen as an example on the extreme limitation of both simulations. In one hand, BES-only simulation needs assumption on airflow parameters, on the other hand AFN-coupled simulation needs additional information on the airflow network components (e.g. crack model of the façade, fan model, etc). In this case, for the AFN-coupled simulation additional information is needed on the airtightness of the façade. Moreover, from the airtightness data, the crack characteristic of the façade should be derived. In the applied model the crack is assumed to be represented by a width and a length (assumed 1 mm and 6 m respectively). At this point, however, there is not enough information to support this assumption.

Turning back to the results, in Table 3.8 a sensitivity of more than 20% is shaded. Applying this information, all of Configurations 1, 4 and 5 have several cases that would require a CFD-coupled simulation. Nevertheless, this information is not enough to decide on which configuration requires further investigation.

Additional information from the results for the different configurations must be used to select which design option has the best overall performance. Table 6 shows that Configuration 1 is outperformed by Configurations 4 and 5. There is no significant difference in comfort performance between Configuration 4 and 5. However, Configuration 4 has a higher heating and a lower cooling demand, while for Configuration 5 this is the other way around. They both have a similar value for the primary energy. Configuration 4 has a maximum heating load that is around 40% higher than Configuration 5. This may result in higher design specifications for the heating equipment for Configuration 4. This is not desirable. From the above discussion, it therefore is concluded that Configuration 5 has the best overall performance.

3.7 BES-AFN-CFD coupled simulation and more

From the evaluation of the results thus far Configuration 5 shows the best performance. Is it necessary that Configuration 5 be simulated with a CFD-coupled simulation? If we use the 20% limit of the maximum deviation, there are several cases that need to be simulated with a CFD-coupled simulation. However, further consideration should be used in addition to the 20% limit value.

Most of the sensitive cases are energy related. If energy is the main consideration then the decision should be based on the primary energy, which represents the total amount of energy. The tables indicate that the primary energy is not sensitive to the convection coefficient. So, even if a CFD-coupled simulation is performed, theoretically this will not influence the primary energy value that is predicted by the AFN-coupled simulation, ±1% which is the maximum deviation from the base condition of the AFN-coupled simulation. With this argument, one therefore can conclude that the results from AFN-coupled simulation are sufficient to answer the design questions for this building. There is no need to do the CFD-coupled simulation.

However if local discomfort is suspected and if comfort considerations are given a higher priority, then another conclusion may be drawn. In that case a CFD-coupled simulation may be necessary.

In the above described example in principle the gas consumption should be simulated at a higher resolution level, considering the high sensitivity to the airflow parameter. However, even with the airflow network model included in the simulation, the result will not give any indication as to how many hours the boiler will work. A higher resolution level should be used to calculate the gas consumption, i.e. by applying explicit plant simulation. This level of resolution, however, is not on the same axis as the airflow.

3.8 Conclusions

This chapter proposes a guideline for the selection of a simulation tool for airflow simulation. The guideline as described here, however, does not intend to fully automate the decision process. Sensitivity analysis is used as a tool, but the decision whether to use higher resolution (and more complex) simulation still considers other factors. The main contribution of this work is that it tries to make a logical scheme to what is usually an abstract and subjective endeavour.

As elaborated earlier, one of the objectives of this thesis is to develop a guideline for coupled simulation, which has been formulated as the Coupling Procedure Decision Methodology (CPDM). Its task is to systematically guide the selection process of resolution level and complexity of the simulation. The novelty of the CPDM is that it covers the whole range of simulation tools and uses the tools according to the need at a specified time.

In my opinion, this is an essential step with regards to the coupled (BES-CFD) simulation because it clarifies for which purpose the coupled simulation is needed at a particular point in the design process. On the basis of this knowledge it can then be decided which parameters and variables need to be exchanged between the coupled tools, and at which time-steps this should take place.

CPDM suggests a rationale for selecting appropriate energy and airflow modeling levels for practical design simulations, which:

- reduces the number of design alternatives to be considered at higher levels of resolution,
- focuses in terms of simulation periods at higher levels of resolution (for example, CFD is only necessary for winter condition),
- indicates whether (de-)coupled BES / CFD simulation will be needed.

Although initially developed for coupled simulation in building airflow, CPDM can be applied generally to all simulation, coupled or otherwise, and with a slight modification, it could also be applied to domains other than airflow. Figure 3.2 could be made in 3 dimensions (or more) to include other domains, e.g. lighting or control system, or plant system.

The whole procedure described by CPDM can be made automatic, provided that the level three decision rule (as discussed in Section 3.3.3) has been formulated. However, the formulation of the decision rules is beyond the scope of this thesis. New developments in this area (e.g. Augenbroe and Park 2005) can be used as the basis to formulate the automatic decision rules.

ESP-r has implemented the sensitivity analysis procedure as part of its uncertainty analysis feature. CPDM can be implemented using the same front-end. The decision rules will act as the back-end, and this needs to be developed in the source code.

Chapter 4

The external coupling

This chapter presents the implementation of the external coupling method. The developments of coupling methods are critically reviewed from the literature. Based on the review, the external coupling method is developed. The summary of the prototypes are presented, along with generic requirements and an example on how to develop the external coupling between BES and CFD with other software.

4.1 Introduction

As mentioned earlier, the coupling between BES and CFD simulations is seen as a way to overcome the limitation of each program. BES and CFD each have their own technical shortcomings; some of the more important ones are:

- For CFD the domain boundary is usually the inside surface of a room. However, it is difficult to predict the corresponding boundary conditions (Beausoleil-Morrison 2000) since these depend on many parameters and variables, e.g. construction details, ambient conditions and HVAC operation.
- In BES, the specification of convective heat transfer is simplified – and its importance often underestimated – by using surface averaged film heat transfer coefficients. Many studies (e.g. Spitler et al. 1991and Lomas 1996) however show that the specification of CHTC has significant impact on the result (e.g. up to 37% difference in energy consumption prediction).

The coupling of BES and CFD lets both programs to solve each other's problem. BES can provide internal surface temperatures of the walls to CFD, while CFD can provide more accurate CHTC for BES. BES can also provide HVAC parameters to CFD (e.g. the supply air temperature and flow rate) by supplying the cooling or heating load.

This chapter reviews the literature on how the coupled BES-CFD mechanism was implemented in previous studies. Based on the review, the external coupling method between BES and CFD is developed. This chapter finishes with specifying generic requirements to implement the external coupling method. Together with an example, these requirements will enable the replication of the implementation of external coupling using any other BES and CFD software.

4.2 BES-CFD coupling mechanism

4.2.1 Basic principles of BES – CFD coupling

The focus point of BES-CFD coupling is in the convection heat transfer on the internal surfaces (Figure 4.1), which is represented by:

$$q_{i,conv} = h_{i,conv}(T_i - T_{i,air}) \qquad (4.1)$$

where:
- $q_{i,conv}$: convective heat transfer (W/m^2)
- $h_{i,conv}$: convective heat transfer coefficient (W/m^{2}K)
- T_i : surface temperature (K)
- $T_{i,air}$: air temperature near the surface (K)

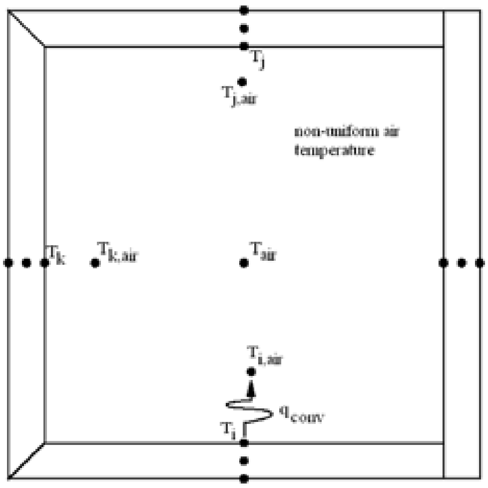


Figure 4.1 Convective heat transfer in non-uniform air temperature

The above equation can be rewritten as:

$$q_{i,conv} = h_{i,conv}(T_i - T_{room}) - h_{i,conv}\Delta T_{i,air} \qquad (4.2)$$

where: T_{room} : mean room air temperature

$\Delta T_{i,air}$: $T_{i,air} - T_{room}$

BES usually assumes the CHTC values using empirical correlations. Some BES packages provide an array of empirical correlations to be used for different scenarios. However, that alone in many cases is not sufficient, as BES uses the well-mixed assumption so that the local variation of surface temperature cannot be captured (Figure 4.2). The BES-CFD coupled simulation is introduced to overcome this problem. CFD will calculate CHTC to be used to calculate the convection heat transfer in BES.

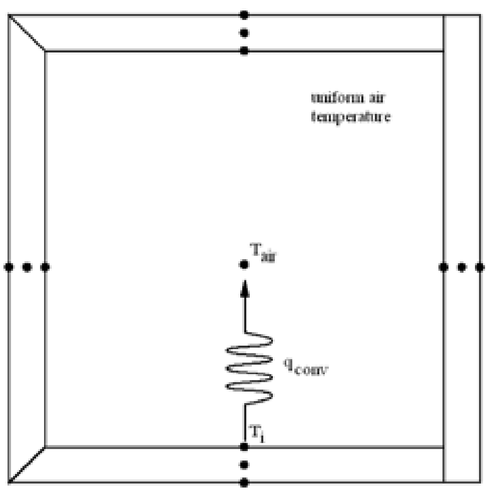


Figure 4.2 Convective heat transfer in uniform air temperature

At this point, there is still an inconsistency that has to be resolved. CFD will always calculate the CHTC as local values with $T_{i,air}$ as the reference temperature (as in Figure 4.1 using equation 4.1). BES on the other hand will use T_{room} as the reference temperature (as in Figure 4.2 using equation 4.2).

If the BES is not capable of including the value of $\Delta T_{i,air}$ (in Eq. 4.2) into its calculation, then there will be a discrepancy as the resulting equation is only the first part of Eq. 4.2, while the second part is missing. If this happens, then the BES and CFD will calculate a different convective heat transfer rate.

Zhai (2003) suggested that for BES packages that cannot accept the value of $\Delta T_{i,air}$ into its convection calculation, a modified version of CHTC should be used. The modified version of CHTC, along with the room temperature as the reference temperature, should give the same convective heat, i.e.

$$q_{i,conv} = h_{i,conv-nom}(T_i - T_{room}) \tag{4.3}$$

Equating the last equation with Eq. 4.1 and rearranging, we have:

$$h_{i,conv-nom} = h_{i,conv} \frac{(T_i - T_{i,air})}{(T_i - T_{room})} \tag{4.4}$$

where: $h_{i,conv-nom}$: modified value of convective heat transfer

The above method in supplying the modified value of CHTC is to ensure that the BES calculates the same amount of convective heat in its calculation.

Zhai (2003) warned about the possibility of having a negative CHTC, as could happen in the following scenario (Figure 4.3). If the CHTC is 4 W/m^{2}K, then using Eq. 4.4 the CHTC$_{nomimal}$ is –1 W/m^{2}K.

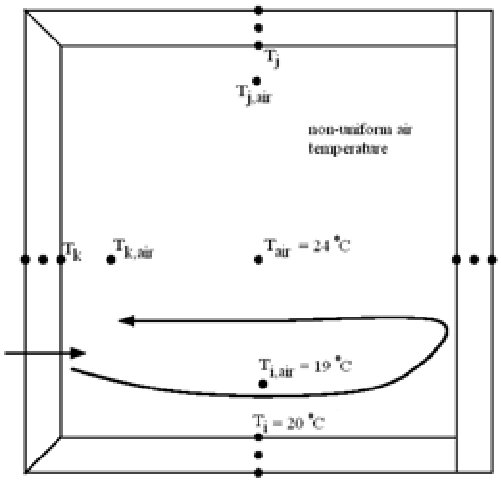


Figure 4.3 Scenario that leads to a negative CHTC

Having a negative CHTC opens a possibility of divergence and instability in the coupled solution. However, as Zhai (2003) concluded, negative CHTC may not always occur since its occurrence only violates the sufficient condition for convergence, not the sufficient and necessary condition. In general, the greater the negative value is the higher the probability of having an unstable and unconverged simulation.

4.2.2 Various implementations

4.2.2.1 Early implementation in ESP-r

The early implementation of BES-CFD coupling in ESP-r was done by Negrao (1995). Three methods of “handshaking” were implemented:

1. Convection coefficient scheme (“Surface Conflation”)

   The thermal domain establishes boundary conditions (BC) for CFD using the surface temperatures calculated on the previous time-step. Once the CFD model converges to a solution, air-to-surface heat transfer is determined from the CFD-predicted flow based on the temperature fields using the log-law wall functions. Surface-averaged convection coefficients for each surface of the zone are then calculated and passed back to the thermal domain.

2. Simultaneous solution scheme (“Integrated Conflation”)

   In the previous scheme CHTC values were calculated by CFD prior to the zone matrix formation. In this scheme the CFD interacts directly with the thermal matrix solver in order to drop (to a degree) the well-stirred assumption. This is accomplished by using CFD to solve the zone air-point temperature and internal surface convection. The heat balances for internal surface nodes and the zone air-point node are rewritten by evaluating the surface convection terms using CFD results. The convection terms are not expressed with surface and air-point nodal temperatures and convection coefficients, but rather the CFD-predicted heat transfer is directly used in the nodal balances. This affects the form of the zone matrix of equations. This method of coupling CFD with the thermal domain eliminates convection coefficients from the zone matrix, which was know to cause numerical problem. However, it does not entirely solve the problem. If CFD inaccurately predicts the surface convection, errors will propagate throughout.

3. Momentum coupling

   This will be explained briefly in Section 4.2.4.

4.2.2.2 Other methods

Zhai (2003) described other methods which is called staged coupling strategy, consisting static coupling process, dynamic coupling process and bin coupling process (Figure 4.4). The selection of the appropriate staged coupling must consider the physics of the problem and the purpose of the simulation.

The static coupling process has static information exchange between BES and CFD on specific time step only. It involves one-step or two-step information exchange between BES and CFD programs, depending on user specification. Because the information exchange is only in limited number of time steps, this coupling strategy can be performed manually.

The dynamic coupling process performs continuous information exchange between the two programs at every time step. This is usually required when both BES and CFD solutions are sensitive to the transient boundary conditions. Three kinds of dynamic coupling processes were identified. The first one is one-time-step dynamic coupling process, which focuses on the BES-CFD coupling at one specific time step of interest. At that time step, the iteration between BES and CFD is performed to reach a converged solution. The second one is full dynamic coupling where BES and CFD exchange information at every time step, and at each time step iterate the result until convergence. This means that both BES and CFD exchange the information for the current time step, and only march the time step when the result converges. The third one is quasi dynamic coupling where BES and CFD exchange information at every time step without iterating the result. This means that BES sends the information to CFD for the current time step, and CFD returns the information to BES for the next time step.

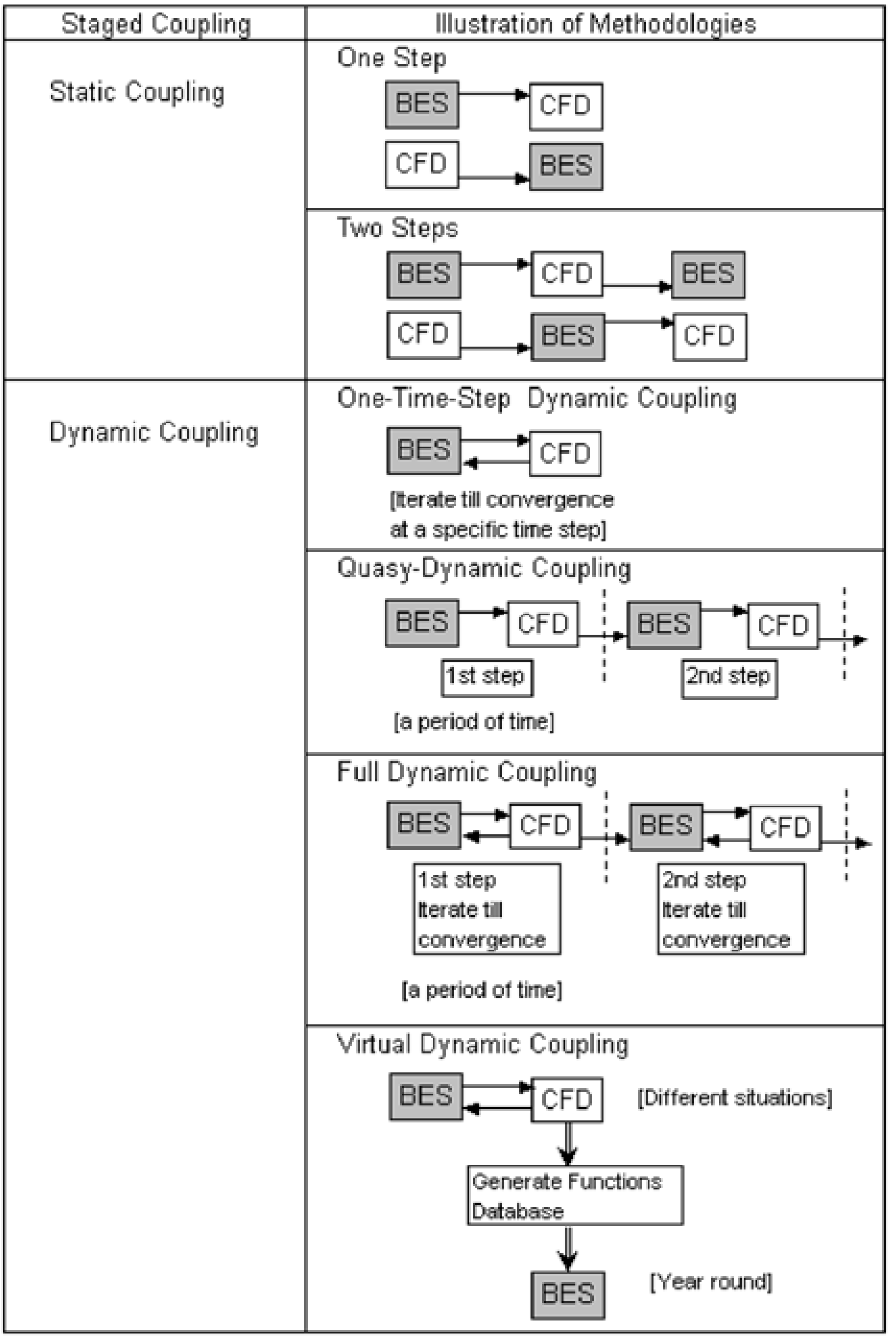


Figure 4.4 Staged coupling strategies (Zhai et al. 2001)

The virtual dynamic coupling (bin coupling) was introduced to reduce the computing cost, especially for long simulation period. CFD (pre)-calculates the airflow based on several scenarios of outdoor condition, and the result was saved into several bins. BES will then use the CFD results during its calculation.

For the purpose of this study, static coupling is not interesting because it can be done manually by the user. Among three types of dynamic coupling, only two are relevant to be explored further, i.e. the quasi-dynamic coupling and the full dynamic coupling. These two types of dynamic coupling are similar to the two coupling methods implemented in ESP-r.

4.2.2.3 Further developments: introducing intelligence

Beausoleil-Morrison (2000) continued the development of CFD coupling within ESP-r. One major development is the introduction of the adaptive conflation method to give some intelligence to the coupled mechanism.

The core of the adaptive method is the gopher run, which is a CFD simulation with the sole purpose of investigating the flow regime around the surfaces. This gopher run is supposed to be fast as it runs on a very coarse mesh and uses the zero equation turbulence model. Based on the result of the gopher run, the coupling controller decides what kind of boundary condition should be sent to CFD.

This is an important development as it reduces the dependence of CFD boundary condition on user input.

Figure 4.5 shows the higher level view of CFD coupling in ESP-r as of the latest development.

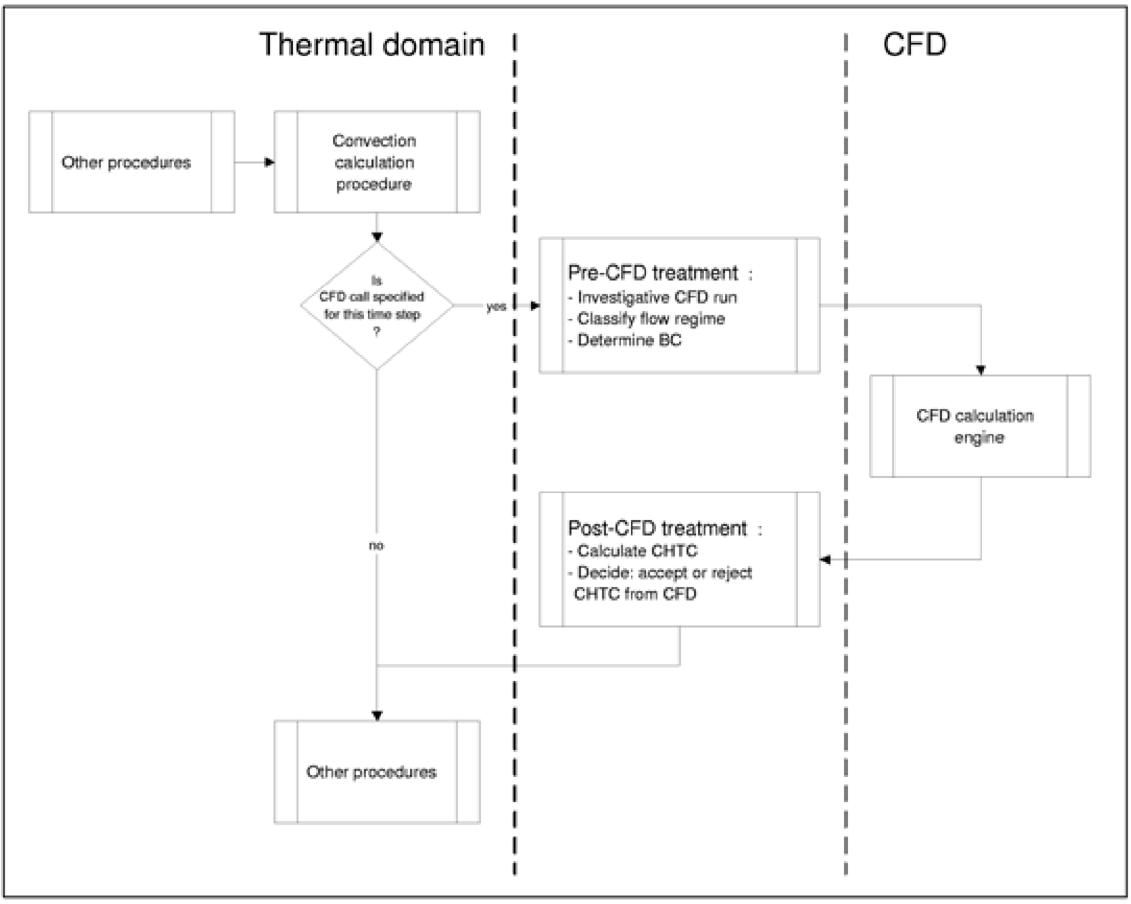


Figure 4.5 Higher level view of coupling mechanism

4.2.3 Exchanged information

In earlier study (Negrao 1995), there is no explicit explanation on what are the possible options for exchanged information. It was taken as obvious that for surface conflation, the exchanged parameters are (1) from BES: wall temperatures and (2) from CFD: convection coefficients, and for integrated conflation are (1) from BES: wall temperatures and (2) from CFD: heat flux.

In later developments though, there are more explicit specifications on what are the exchanged parameters. Beausoleil-Morrison (2000) defines 10 possible combinations of exchanged parameters between BES and CFD. The mechanism to select the appropriate combination has been implemented in ESP-r, even though there is no study on how is the stability of each possible combination.

Zhai (2003) proposed 6 combinations of exchanged parameters, and studied the stability of each combination. These are:

1. From BES: wall temperature; From CFD: $h_{i,conv}$ and $\Delta T_{i,air}$
2. From BES: wall temperature; From CFD: $h_{i,conv\text{-}nom}$
3. From BES: wall temperature; From CFD: $Q_{i,conv}$
4. From BES: $Q_{i,conv}$; From CFD: $h_{i,conv}$ and $\Delta T_{i,air}$
5. From BES: $Q_{i,conv}$; From CFD: $h_{i,conv\text{-}nom}$
6. From BES: $Q_{i,conv}$; From CFD: $Q_{i,conv}$

Zhai focused the study on methods 1, 3, 4, because methods 1 and 2, and also methods 4 and 5 are “substantially equivalent”, and method-6 is not “workable”. Based on some simplifications, the study performs mathematical verification and also numerical experiments. The findings of the study are as follows:

1. Methods 1, 3, and 4 represent three different expressions of one original equation group, which is mathematically identical so that they can theoretically produce the same solutions with the same set of boundary conditions.
2. Method 1 is better than method 3 as method 3 has more conditions to get a converged solution. Method 1 also tends to be more stable and proceed faster in the simulation. It should be noted though that this may not be true on real problems where the simplification used in the study does not apply.
3. Method 4 gives some difficulty in controlling the indoor air temperature in CFD. This method sends $Q_{i,conv}$ from BES to CFD instead of surface temperature. Therefore, even if the heat balance in BES and CFD are satisfied, the temperature distribution can be different between BES and CFD.

It is interesting to note that Beausoleil-Morrison (2000) has not tested the stability and convergence of each method he proposed, but the study gave some indications on which method should be used for a certain type of flow, and a decision mechanism has also been implemented in ESP-r. Zhai (2003) on the other hand has verified and tested the proposed method, but the study only gives a general indication as to which method are suitable for any particular flow.

4.2.4 Momentum coupling

As mentioned earlier, momentum coupling is one of the schemes explored by earlier study (Negrao 1995). This is a handshaking method between the air flow network and CFD; hence there is no interaction between CFD and the thermal domain. This approach is complementary to the thermal coupling.

In other scheme involving thermal domain the mass flow network (mass flow rate) is assumed to be unaffected by the inside zone air flow, the present coupling supposes that both domains are dependent on each other, and therefore a direct interaction between the two systems must exist. This means that the air flow within the zone influences the flow in other parts of the building and vice versa.

A single air flow network node is replaced by a CFD domain (Figure 4.6) to drop the assumption of well-mixed conditions for a zone (for the purposes of air flow modelling; however, the well-stirred assumption is still in effect in terms of the thermal model). New connections are added to the air flow network to link the CFD domain to the network (nodes A, B and C in Figure 4.6), while connections to the removed node are eliminated. The network air flow domains establish BC for CFD (temperatures and flow conditions at diffusers, extracts, and other openings). Once CFD converges to a solution, the CFD predicted air flows into and out of the zone are passed to the network air flow solver, where they are treated as sources or sinks of mass. The network is then solved in its usual manner to determine the flow through the remaining connections in the network.

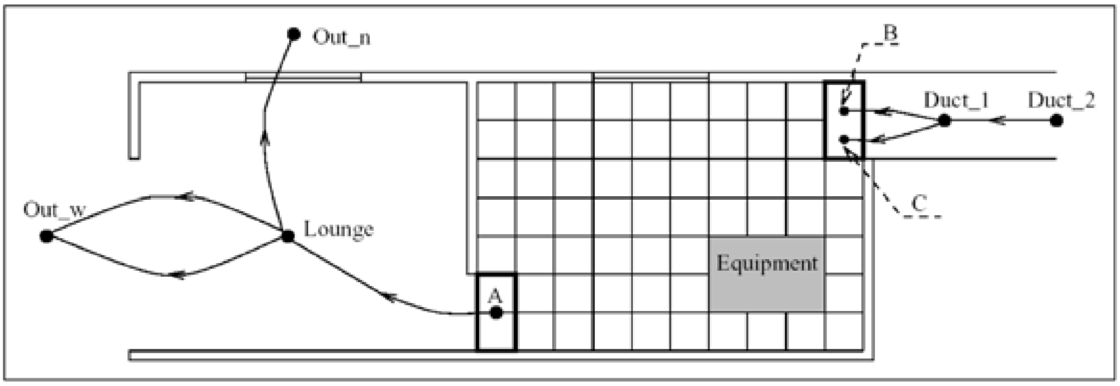


Figure 4.6 Momentum coupling between CFD and airflow network (Negrao 1995)

Even though the coupling between AFN and CFD (i.e. momentum coupling) is also addressed in the guideline described in Chapter 3, its implementation for external coupling is out of the scope of this thesis.

4.3 Some details on CFD-BES coupling in ESP-r

4.3.1 CFD Invocation

CFD is invoked by thermal domain on every time step within the time range specified by the user input. Depending on the boundary conditions for the CFD simulation, there are two modes of CFD coupling:

1. Un-adapted mode
2. Adapted mode

The difference between the two modes is in how the CFD boundary condition is set. In un-adapted mode, the CFD boundary conditions are taken from the user input. In adapted mode, the CFD boundary conditions (and other simulation settings) are set automatically, and this will be explained in the following section.

Figure 4.7 shows the two-way adapted conflation mechanism which can be regarded as an advanced and sophisticated mechanism in the BES-CFD coupled simulation.

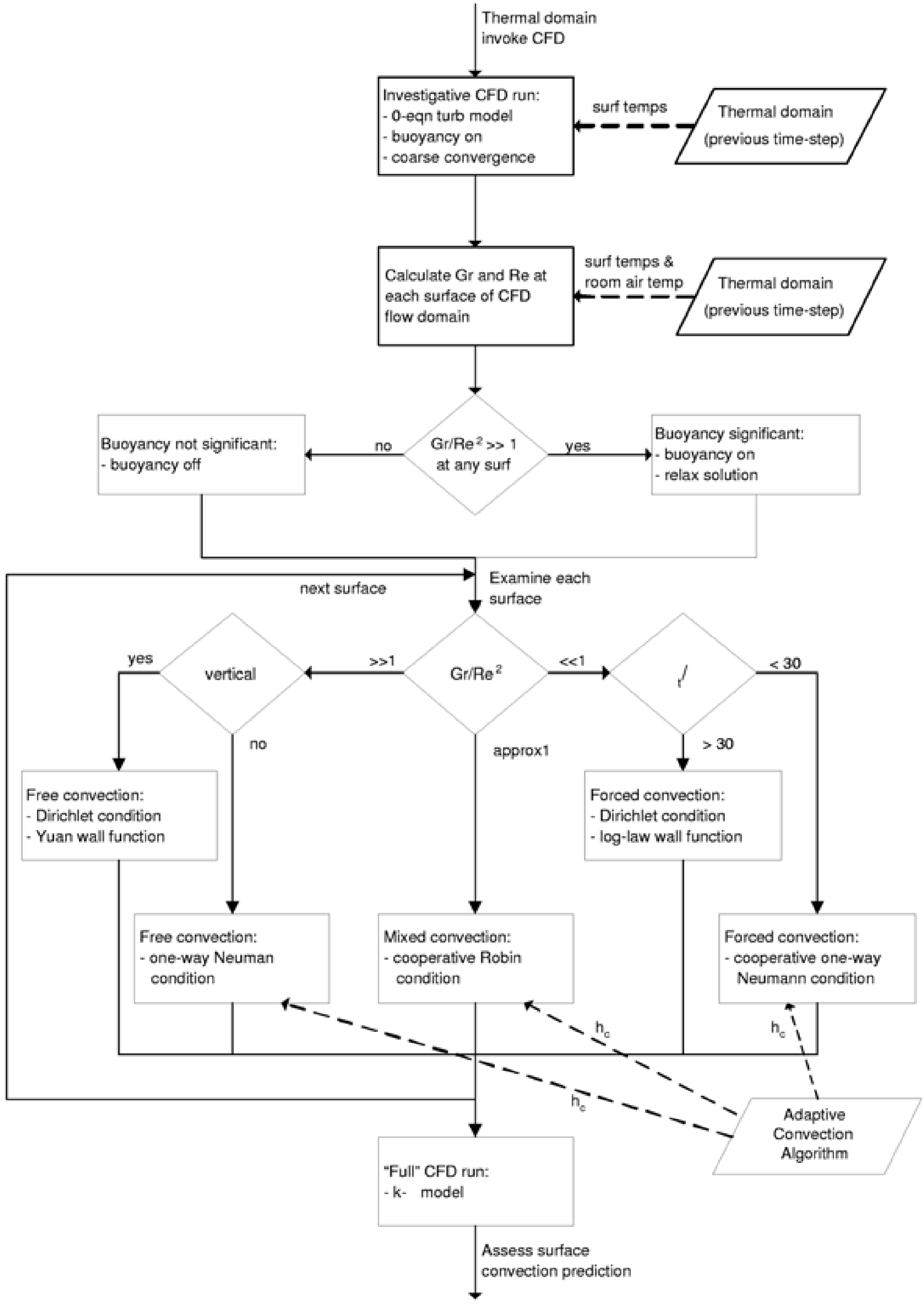


Figure 4.7 Two-way adapted conflation

4.3.2 Components of the coupling mechanism

On every time step, during the calculation of the convection heat transfer coefficient (CHTC) of internal surfaces, the thermal domain checks whether there is any CFD call defined for that time step. If not, it continues with another mechanism for defining the CHTC of the internal surfaces (i.e. using one of many available empirical correlations). If yes, it will invoke the coupling controller to derive the CHTC from a CFD simulation. The coupling mechanism consists of (1) pre-CFD treatment, (2) the (final) CFD simulation and (3) post-CFD treatment (as summarized in Figure 4.5 and detailed in Figure 4.7).

The pre-CFD treatment involves an investigative CFD simulation. This investigative CFD simulation (the so-called “gopher run”) is a simple CFD simulation (with coarse mesh and simple turbulence model) that will classify the flow regime near each surface.

The end result of the gopher run is a set of non-dimensional numbers for each surface, indicating the flow regime of airflow on the surface: either forced, natural, or mixed convection. Based on the classification of airflow regime, the coupling controller decides which boundary conditions are applied for the final CFD simulation.

The final CFD simulation uses the standard k-ε turbulence model. For the final CFD simulation, the coupling controller sends the following information:

1. wall surface temperature
2. which wall function to use (log law or Yuan)
3. whether the CHTC derived from an empirical correlation should also be sent to CFD
4. what reference temperature should be used in CHTC calculation in CFD.
5. supply air temperature and flow rate, if there is an HVAC system assumed in the simulation.

After the final CFD simulation, the post-CFD treatment will calculate the CHTC for each internal surface based on the CFD result, i.e. the $CHTC_{CFD}$. The calculated $CHTC_{CFD}$ is then compared with a CHTC value that was calculated by the default ESP-r correlation. If $CHTC_{CFD}$ falls within a certain predefined range, then it will be accepted and passed to the thermal domain. If not, it will be rejected and the thermal domain continues the calculation using the CHTC derived from the ESP-r’s default empirical correlation. The post CFD treatment is described in Figure 4.8 and can be expressed in the following equation:

$$0.1\ CHTC_{empirical} < CHTC_{CFD} < 10\ CHTC_{empirical} \qquad (4.5)$$

where: $CHTC_{empirical}$: CHTC from empirical correlation

$CHTC_{CFD}$: CHTC from CFD calculation

In my opinion, the post-CFD treatment to filter the $CHTC_{CFD}$ value based on $CHTC_{empirical}$ is a very good concept. However, as will be shown the validation study (Section 5.4.2.5), the mechanism is limited by several factors:

1. The number of empirical correlations being implemented in the program. If the relevant empirical correlation is not available, the post-CFD treatment is useless.
2. The way the empirical correlations are implemented in the program. The implementation of Fisher correlation (one of the empirical correlation to calculate CHTC that has been implemented) in ESP-r is an example that even if we have the relevant correlation, the implementation can have a trap (see

Section 5.4.2.5) where the result of CHTC calculation will be far from accurate.

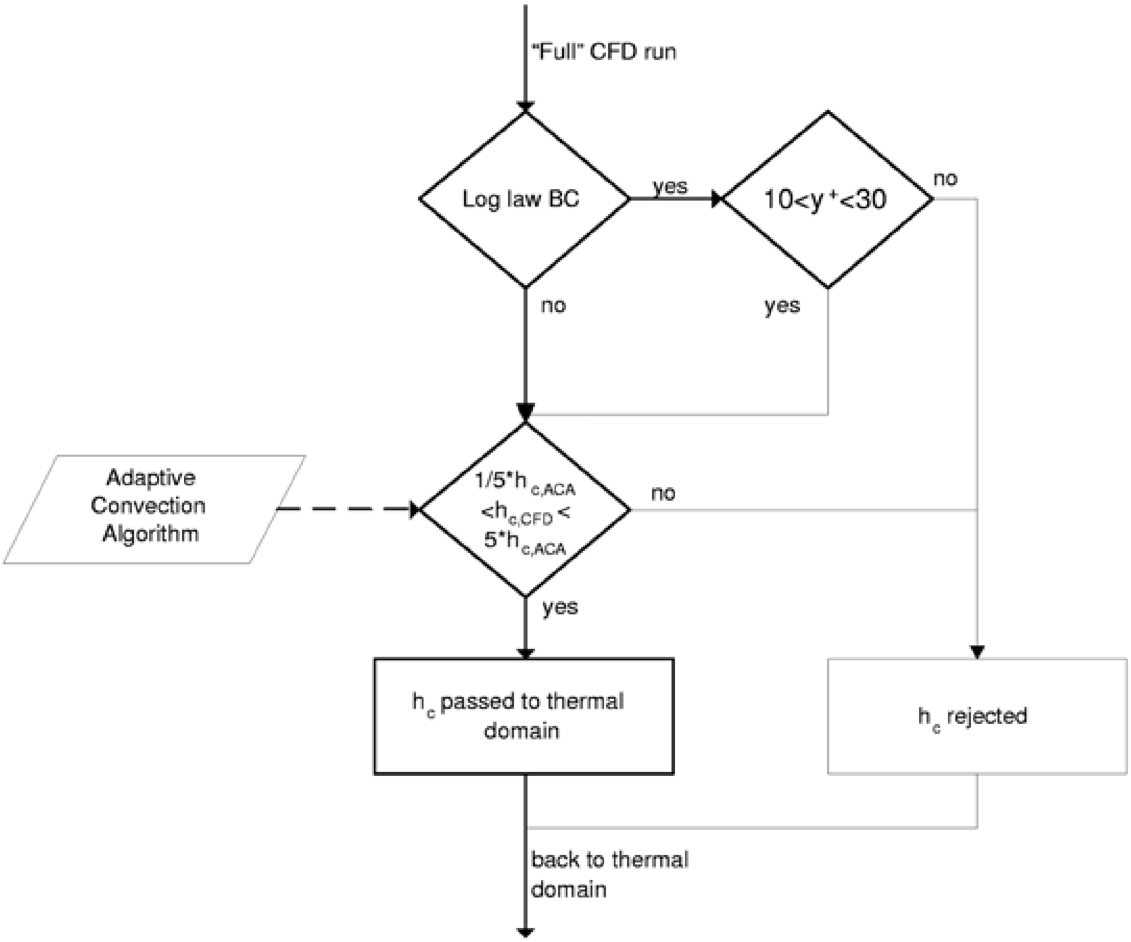


Figure 4.8 Post-CFD treatment

4.3.3 CHTC definition

ESP-r uses the so-called co-operative approach to calculate the CHTC. CTCH is calculated using the following equation (ESRU 2003):

$$h_{i,conv} = \left| \frac{q_{i,conv}}{(T_i - T_{room})} \right| \tag{4.6}$$

where: $h_{i,conv}$: $CHTC_{CFD}$ (W/m^{2}K)

$q_{i,conv}$: convective heat transfer calculated by CFD (W/m^2)

T_i : surface temperature (K)

T_{room} : air room temperature (K)

The approach is actually similar to $CHTC_{nominal}$ method (Eq. 4.4) with two main difference:

1. CFD does not explicitly calculate the $CHTC_{CFD}$. The CFD sends the convective heat transfer ($q_{i,conv}$) to BES where Eq. 4.6 is actually calculated. Beausoleil-Morrison (2000) implemented eight different ways of calculating the convective heat transfer on the wall, depending on the boundary condition type set on the wall.
2. The $CHTC_{CFD}$ is always positive because the absolute value is taken.

Taking the absolute value ensures that the $CHTC_{CFD}$ is always positive. However, it cannot ensure the correct direction of the convective heat transfer. Consider the scenario of having the negative CHTC (Figure 4.3). Using temperature difference of ($T_i - T_{i,air}$), the CFD predicts a positive $q_{i,conv}$, say 4 W/m^2, which means heat injection. When the $q_{i,conv}$ is sent to BES and used to calculate the CHTC using Eq. 4.6, the $CHTC_{CFD}$ is positive (i.e. 1 W/m^{2}K) because the absolute value is taken. And when the positive value is used to calculate the convective heat transfer in BES, the result will be a negative $q_{i,conv}$ which means heat extraction. There will be an inconsistency in the direction of the flow between the CFD prediction and the BES prediction.

On the other hand, by allowing $CHTC_{CFD}$ to have a negative value, $CHTC_{nominal}$ method ensures the same convective heat transfer on the surface. In this example, if the CHTC is allowed to be negative, the CFD and BES prediction will be the same, i.e. heat injection of 4 W/m^2.

4.4 Implementation of external coupling

4.4.1 Main parameters

4.4.1.1 Which method to use for external coupling?

As mentioned earlier, only two methods that is interesting for coupled simulation, if the dynamic of the simulation needs to be captured. The surface and integrated coupling (as they are called in ESP-r) or quasy-steady dynamic coupling and full-dynamic coupling (as they are called in Zhai 2003). The term “Surface Conflation” comes from the fact that the coupling involves parameters in the “surface” of the model (i.e. wall), and the “surface” of computation (i.e. exchanges in boundary condition without affecting the matrix formation in either simulation).

The surface coupling (the quasi-steady dynamic coupling) is selected as the method to be implemented in the external coupling because of the following reasons:

1. The changes in the source code (of BES) can be kept to minimum. The most important change is to enable the program to dump the boundary conditions for CFD to a text file, and then to read the results of CFD simulation. The full-dynamic coupling will have more changes to the code as it requires the iteration between the two domains within the time step. The integrated coupling, although it is similar to full dynamic coupling, is even more complicated to be implemented with external coupling, as it involves the exchange of parameters every a certain iteration of CFD calculation where the result of CFD is directly changes the matrix calculation.
2. Even though the full-dynamic coupling is more accurate then the quasi-steady dynamic coupling, Zhai (2003) found that the quasi-steady dynamic coupling can have similar predictions as the full-dynamic coupling. Beausoleil-Morrison 2000 argued that the two methods should produce similar results provided that the time step is sufficiently small. However, there is no further explanation on how small should the time step be. Zhai (2003) indicates that the minimum time step is 2 hours.

4.4.1.2 Which data to be exchanged?

For external coupling the following data exchange will be used:

- From BES to CFD:
  - wall temperature
  - heat extraction/injection (if applicable)
- From CFD to BES:
  - $CHTC_{nominal}$ as in Eq. 4.4.

The reasons for this are as follows:

1. Zhai (2003) suggested that this option is more stable than the others.
2. The $CHTC_{nominal}$ is easily defined in any BES package. This is an important consideration because the external coupling should be generally applicable to all BES packages.

4.4.1.3 What is the frequency of the data exchange?

As mentioned earlier, Beausoleil-Morrison 2000 argued that the quasi-steady dynamic coupling should produce similar results as the full-dynamic coupling provided that the time step is sufficiently small. However, there is no further explanation on how small should the time step be. Zhai (2003) indicated that the minimum time step is 2 hours.

4.4.2 Prototypes evolution

The prototypes are summarized below to demonstrate the various possibilities explored before coming to the current form.

4.4.2.1 Prototype 1

In the first prototype, the CFD calculation engine (in the right hand side of Figure 4.5) is changed with an external CFD program. The other mechanisms remain unmodified.

In this prototype, there was no direct contact between the external CFD program with the BES. The BES is required to have its internal CFD capability, although its internal CFD engine is not used. The external CFD program will actually do the CFD simulation, and then transfer the field values into the CFD variables kept by the internal CFD module in BES.

The main advantage of this prototype is that it is simple to implement as there is no data conversion issue to handle. The field values (pressure, air velocity, air temperature, and turbulence parameters) are simply transferred from external mesh to the internal mesh kept by internal CFD module of the BES.

The disadvantages of this prototype is that the mesh of the external CFD package should always be made identical with the internal mesh in order to avoid interpolation error that will occur should this two meshes be different. This will inhibit the full utilization of the (supposedly) more powerful meshing capabilities of the external CFD package.

Furthermore, in terms the view that external coupling should be made applicable to wide range of BES and CFD programs, the requirements that the BES should have its own internal CFD module is certainly not acceptable.

4.4.2.2 Prototype 2

In this prototype, the external coupling takes over the full CFD simulation. All other mechanisms remain unmodified. This means that the gopher CFD run is performed by the internal CFD module of the BES.

There were some tests performed to assess the viability of the whole mechanism (see Section 5.2.5). The main question is whether to keep the pre-CFD treatment (i.e. the gopher run). The tests findings show that the use of pre-CFD treatment for external coupling at this stage is not relevant. The decisions that are made on the basis of gopher run's results are only relevant if the full CFD simulation uses the standard k-ε turbulence model. As can be seen Section 5.2.5, the combination of standard k-ε turbulence model with fine mesh leads to long simulation hours.

The above consideration leads to the last prototype: the working prototype.

4.4.2.3 Prototype 3

Adapted coupling is a sophisticated mechanism. However, it is too complex for the purpose of showing how the external coupling can be implemented. For this reason, a simpler approach as is now implemented (without the gopher run and time dependent turbulence model selection) can be used.

Apart from the above reason to skip the pre-CFD treatment, a simplified prototype is really needed to highlight the "bare-bone" external coupling mechanism without additional mechanism. By studying the performance of this minimum model, a solid ground can be established for further development by adding various mechanisms.

The current prototype skips the gopher run and uses the indoor zero-equation turbulence model. The reasons to use the indoor zero equations turbulence model are:

1. it uses less computing resource than the standard k-ε turbulence model.
2. it does not make use of wall functions.
3. it has been successfully used for the coupling of CFD and energy simulation (Chen et al. 1999).

The following mechanism reflects the up-to-date status on external coupling between CFD and BES:

1. During the calculation of the CHTC for the internal surfaces BES checks if a CFD simulation is specified for the current time step. If not, it will continue to calculate the CHTC based on user input.
2. If yes, the BES will invoke the coupling controller which will call the external CFD program to run the CFD simulation (using the zero equation turbulence model).
3. After the simulation, the CFD program calculates the CHTC for each internal surface and sends the result back to the coupling controller.
4. the CHTC can be explicitly defined using the following equation (Chen and Xu 1998):

$$h = \frac{\mu_{eff}}{\mathrm{Pr}_{eff}} \frac{c_p}{\Delta x} \tag{4.7}$$

where: h : CHTC (W/m^{2}K)

μ_{eff} : effective viscosity (kg/m s)

Pr_{eff}	:	effective Prandtl number (=0.9), dimensionless
c_p	:	specific heat (J/kg K)
Δx	:	distance between the surface to the adjacent cell (m)

5. The CHTC values are then converted into $CHTC_{nominal}$ using Eq. 4.4. The $CHTC_{nominal}$ are sent back to BES.
6. The new CHTC values received from CFD are assessed in BES. If the CHTC falls within pre-defined criteria, BES will use it for further calculation, otherwise BES will use its own CHTC value calculated by empirical correlation.

By skipping the pre-CFD treatment, the current implementation is less intelligent compared to the existing infrastructure in ESP-r. However, it is important to note that it is not a big step to incorporate the gopher run into the current implementation. And once it is done, the whole scheme of adapted coupling can be replicated.

4.5 Software development specification

4.5.1 Generic requirements

Below are the generic requirements that must be met by the BES and CFD program to be able to perform the external coupling method.

4.5.1.1 Ability to read and write the required data

Both programs should be able to read the required data. That means that the BES should be able to accept CHTC value as an input, and CFD should be able to accept wall temperatures (and heat injection or extraction, if applicable).

With the mechanism as summarized in Section 4.4.1.1 above, there will be no problem with the CFD as all of the input data is read before every CFD simulation is commenced.

The case is different for the BES, as the CHTC values must be read on every time step during the simulation. In general, any BES program can accept user-defined CHTC value as an input ***before*** the simulation commenced, but usually BES cannot accept user-defined CHTC value ***during*** the simulation. Most of BES program will need some changes in the source code to allow this.

The same consideration also applies for the writing of the data. Both programs should have the ability to write the data to a text file. This means the BES should be able to write the wall temperature (and the heat extraction or injection), and the CFD should be able to write the CHTC.

Implicit to this requirement is the ability of the program to calculate the necessary parameters.

1. Surface temperature: all BES program should be able to produce this parameter.
2. Heat extraction/injection: all BES program should be able to produce this parameter. However, this information cannot be directly used by CFD. To be useful for CFD, this information must be converted into other set of information by assuming the HVAC system used. For example, if radiator is assumed, the heat injection should be converted into heat flux on the radiator surfaces. Or, it can be converted into supply air temperature, exhaust air temperature and the air flow rate. The conversion of this data can be made inside BES (which requires access to source code), in an external script outside BES and CFD, or inside CFD (through user-defined function).

3. CHTC: all CFD program should have this data, although it is possible that it is not directly calculated. The CFD program should have a way, either by changing the source code or by user-defined function, to explicitly define the CHTC.

Again, the writing of the data to a text file will not be a problem for CFD as it happens right before the end of every CFD simulation so that the CFD can simply write and exit. The BES has a different situation. After dumping the boundary conditions information to the CFD, It has to stop and wait for the CFD to finish, before resuming the simulation to the next time step. Most BES programs will need some changes in the source code to allow this.

4.5.1.2 Access to source code for master program

The master program is the program that takes control of the overall coupling mechanism, and this master program should have the capability of calling other programs involved in the mechanism. With the mechanism as summarized in Section 4.4.1.1 above, the BES should have this capability. Some changes in relevant section of the source code should be made.

For BES code that has internal coupling capability this call should be made in place where the call to the CFD calculation engine is made. For BES code that does not have the internal coupling capability, the place to make this call is before the calculation of convection on the internal surface, after the empirical CHTC (or default CHTC value) has been defined.

4.5.2 Implementation using ESP-r and Fluent

This section will not discuss in details how the implementation has been done. The detailed description of the implementation has been documented in other report (Djunaedy 2004). This section will give a general overview on how this was done in ESP-r and Fluent so that anyone would be able to replicate the effort with other software.

4.5.2.1 Models preparation

At this point, a common model for both BES and external CFD program does not exist. For this reason, there will be two models in the external coupling simulation, each of them can only be read by the corresponding program. When building the models it is important that both models represent the same problem. The relevant surfaces where the data exchange is needed should also be clearly identified.

4.5.2.2 Changes in ESP-r

There is no change in ESP-r main configuration file to use external coupling. The only change is in the CFD configuration file, where one key word is included in the first line. After reading this keyword, the whole CFD configuration is not used.

In the source code, there are 4 changes:

1. In the CFD calculation manager (i.e. subroutine CFMNGE), add a check before calling the CFD calculation engine (i.e. subroutine CFCALC). If the external coupling is selected, then call the new subroutine CFXTRN; otherwise call the internal CFD calculation engine.
2. Create new subroutine CFXTRN that manages the external coupling from within ESP-r. The main functions are:
   i. Calling (new) subroutine to dump the input to external CFD.

ii. Calling the coupling controller script.

iii. Calling (new) subroutine to read the output from external CFD.

3. Create new subroutine BS2CFXTRN that dumps the boundary condition for Fluent. The main functions are:

   i. Dumping wall temperatures to text file.

   ii. Converting the heat injection or extraction into meaningful information for CFD by assuming a certain HVAC system.

4. Create new subroutine CFXTRNHTC that reads the CHTC value from Fluent. The main function is:

   i. Reading the CHTC value from a text file.

4.5.2.3 Coupling controller

The coupling controller is actually a script with 3 main functions:

1. To manipulate the output from ESP-r and compose a Fluent input file from it.
2. To invoke Fluent and feed the Fluent input file.
3. To manipulate the output from Fluent and compose it in the format recognized by ESP-r.

It is important to note that this script functions as a bridge between the two models. The west wall can be called wall01 (and referred to as TS[1] in the variable array) in BES, and at the same time it is called wall13 (and referred to as WALL[13] in the variable array) in CFD. This gap is one of the risks in using external coupling, and the coupling script has to ensure that this gap is bridged.

This coupling controller is called from ESP-r, and ESP-r process stops until this script finishes.

4.5.2.4 User-defined function in Fluent

It is not necessary to have the source code of Fluent. Additional functionalities can be made through user-defined function. The following are the main tasks of the function:

1. Providing the indoor zero-equation turbulence model (Chen and Xu 1998)
2. Calculating the $CHTC_{nominal}$.
3. Dumping the $CHTC_{nominal}$ to a text file.

4.5.2.5 Coupling mechanism

The following process shows the coupling mechanism which is invoked every time step when the external CFD call is made:

1. ESP-r dumps the boundary conditions for CFD simulation which consists of wall temperatures and heat injection or extraction. The heat injection or extraction is usually converted to airflow rate and/or air temperature of the supply air by assuming a simplified HVAC system.
2. ESP-r calls a Unix script that will act as the coupling controller.
3. The coupling controller reads the text file from ESP-r and converts it to the format recognized by Fluent.
4. The coupling controller calls Fluent and supply the newly composed input file.

5. Fluent runs the CFD simulation as per instruction in the input file. Part of the instruction is for Fluent to dump an output file containing the CHTC values of the walls.
6. When Fluent exits, the coupling controller reads the text file dumped by Fluent, and converts it to the format recognized by ESP-r.
7. The coupling controller stops and return to ESP-r
8. ESP-r reads the file prepared by the coupling controller, and extracts the CHTC values.
9. ESP-r checks the $CHTC_{CFD}$ value against the $CHTC_{empirical}$. If the values fall within the criteria, then the $CHTC_{CFD}$ value will be accepted, otherwise the $CHTC_{empirical}$ will be used for further calculation.

Chapter 5

Validation

This chapter reports the validation of external coupling between computational fluid dynamics (CFD) and building energy simulation (BES). The methodology and the scope of validation work are summarized. Three validation cases are presented. The results show that the external coupling shows a good agreement with both experimental data and earlier simulations using internal coupling.

5.1 Introduction

5.1.1 Background

For CFD simulations, the definition commonly used for ***validation*** is "solving the right equations" (Roache 1997). More formal definition is (AIAA 1998):

> *the process of determining the degree to which a (CFD) model is an accurate representation of the real world from the perspective of intended uses of the model.*

Chen (2001) revised the above definition to make it more relevant in end-users perspective where they usually are not involved in CFD code development:

> *Validation is how one can demonstrate the coupled ability of a user and a CFD code to accurately conduct representative indoor environmental simulations with which there are experimental data available.*

It is important to note the difference between validation and verification. The definition usually used for ***verification*** is "solving the equations right" (Roache 1997) or more formal definition is (AIAA 1998):

> *the process of determining that a (physical/mathematical) model implementation accurately represents the developer's conceptual description of the model and the solution of the model.*

The difference is put clearly below (Roache 1997):

> *The code author defines precisely what partial differential equations (PDEs) are being solved and demonstrates convincingly that they are solved correctly—that is, usually with some order of accuracy and always consistently, so that as some measure of discretization Δ (e.g. the mesh increments) approaches zero, the code produces a solution to the continuum PDEs; this is verification. Whether or not those equations and that solution bear any relation to a physical problem of interest to the code user is the subject of validation.*

Code verification process is not described in this thesis as it involves less interesting questions (e.g. does BES send the correct numbers? does BES use the correct CHTC values?) than validation. This study focuses on whether the external coupling mechanism described earlier in this thesis can represent reality.

It is also important to note that this work is not a validation for CFD or BES. It is the coupled mechanism that is going to be validated. Both CFD and BES program (on its own) are assumed to be (and in fact they are) well validated. For external coupling, the validation is needed to achieve confidence that the external coupling mechanism can perform as good as the internal coupling.

5.1.2 Methodology

Based on earlier studies (Bloomfield and Pinney 1990,Judkoff 1983), The PASSYS Project (PASSYS 1994) described different methods of validation:

1. Theory and source code checking: evaluation of alternative algorithms/models and code debugging
2. Analytical tests: comparison of predicted results with exact solutions.

3. Inter-model comparison: comparison of target program with several other target programs.
4. Sensitivity analysis: internal consistency and quality assurance checks.
5. Empirical validation: comparison with carefully planned and measured data.
6. Uncertainty evaluation: determination of confidence intervals on predicted data sets.
7. Recommendation of modifications: based on the above activities.

Figure 5.1 shows the overview of the PASSYS validation methodology. This study does not cover the single process validation as it has been covered in numerous studies conducted earlier either for the BES or CFD package used in this study.

This study concentrates on the whole model validation which aims to investigate whether a model can describe the reality in a correct way. Such an approach is not limited to the isolated process in simple cases, as with analytical validation. Such an approach should in principle compare a “true” model of the reality (as captured by the experiment) with a mathematical model in the program.

The inter-model comparison and the empirical validation is the methodology used throughout this study. Inter-model comparison is performed by comparing the external coupling with internal coupling simulations. Several high quality data were used for the empirical validation.

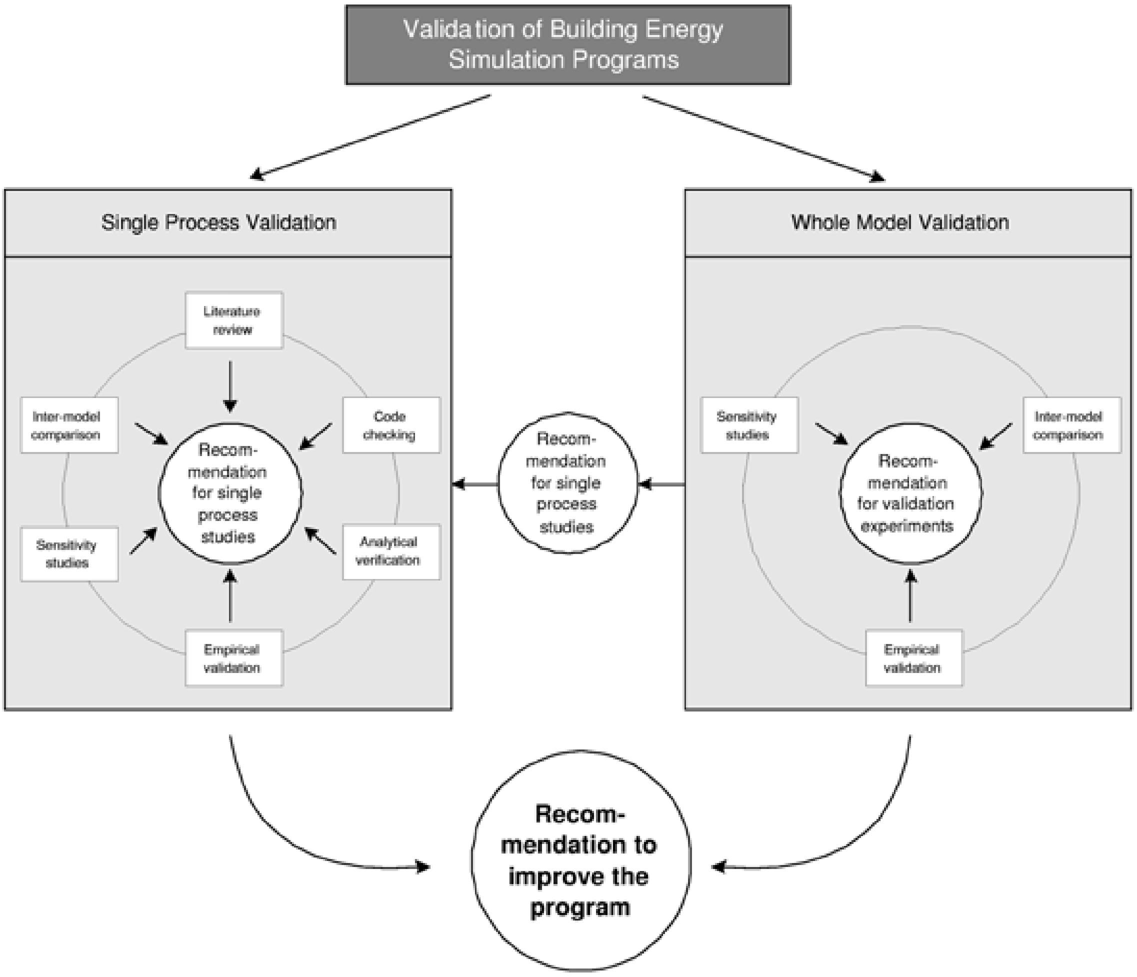


Figure 5.1 The principle of the PASSYS model validation methodology (PASSYS 1994)

Figure 5.2 shows the methodology used in this validation study. The selected cases should have at least the experimental data, and preferably they should also have the simulation work, either CFD-only simulation or CFD-coupled simulation.

From the description of the experiment, the geometry of the computer model was built, and simulation setting to replicate the experimental condition was set. Some initial simulations were run for every model for calibration purpose, to see whether the geometry or the simulation setting has been properly defined. If the results of the calibration do not correspond to the correct geometry or simulation settings, then the model description would be refined.

Once the model geometry and simulation setting has been established, the simulation can be run using either external coupling or internal coupling, or both. The results of the new simulations can then be compared with earlier simulation studies, and also with the experimental data.

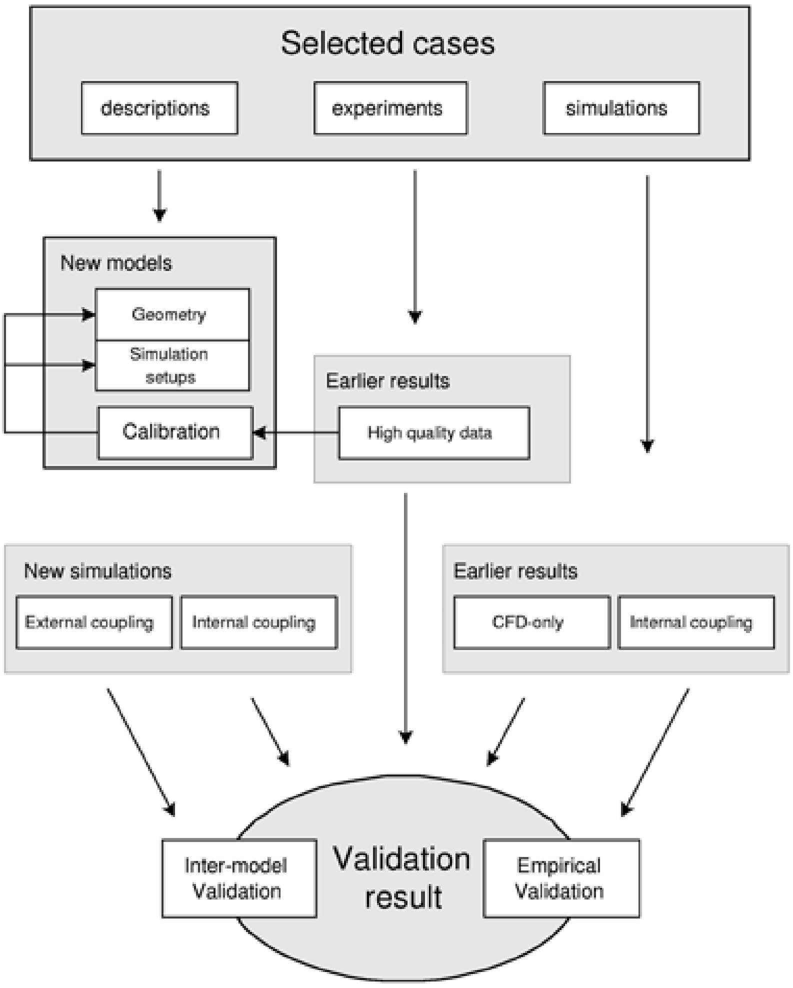


Figure 5.2 Validation methodology used for this study

One important step in the end of validation cycle is the improvement to the existing program (or, in this case, the coupling procedure) based on the validation results. Throughout the validation studies, the prototype proposed in this thesis has evolved to its final form. Even after the last validation case has been completed, some areas of improvements are still identified.

5.1.3 Case selection

The cases were selected from a pool of cases taken from published works. The focus is on cases reported sensitive to the definition of the CHTC. Furthermore, the cases should have been used for validating the internal coupling between CFD and energy simulation. Preferably there should also be CFD-only studies.

Based on the above criteria, the following cases have been selected for validation of external coupling:

- Case 1: IEA Annex 21 test cell (UK)
- Case 2: IEA Annex 26 experimental atrium (Japan): free floating
- Case 3: IEA Annex 26 experimental atrium (Japan): with air conditioning

Table 5.1 gives an overview of the experimental data and the availability of the simulation results.

For Case 1, there is no measurement data. The case was selected simply because there are several studies on this case using internal coupling. Even if there is no data on air movement, it is interesting to make comparison between internal and external coupling. Of course there will be no empirical validation for the air movement, but inter-model comparison can be performed.

The cases were also selected to cover several HVAC systems (radiator and all air system), and several flow type (natural convection, mixed convection). With that kind of coverage, it is expected that the validation study can give confidence in the applicability and accuracy of the external coupling.

Table 5.1 Previous studies of selected case

	Case 1	Case 2	Case 3
Description of the case	Lomas et al. 1994	Ozeki et al. 1996 Heiselberg et al. 1998	Ozeki et al. 1996 Heiselberg et al. 1998
CFD-only simulation study	None	Ozeki et al. 1996 Heiselberg et al. 1998 Schild 1997	Ozeki et al. 1996 Heiselberg et al. 1998
Internal coupling simulation study	Negrao 1995 Zhai 2003	Chen et al. 1999	Chen et al. 1999 Zhai 2003

5.2 Case 1: IEA Annex 21 Test Cell (UK)

5.2.1 Case descriptions

The test cell under investigation is located in Bedfordshire, UK. Figure 5.3 shows the site layout and the situated test cells. The site has eight semi-detached rooms, which have a lightweight, timber framed, construction. These rooms have interchangeable glazing panels in the south walls, and the one used for the current study has a double glazed panel. A detailed description of the site and the test room can be found in Lomas et al. 1994.

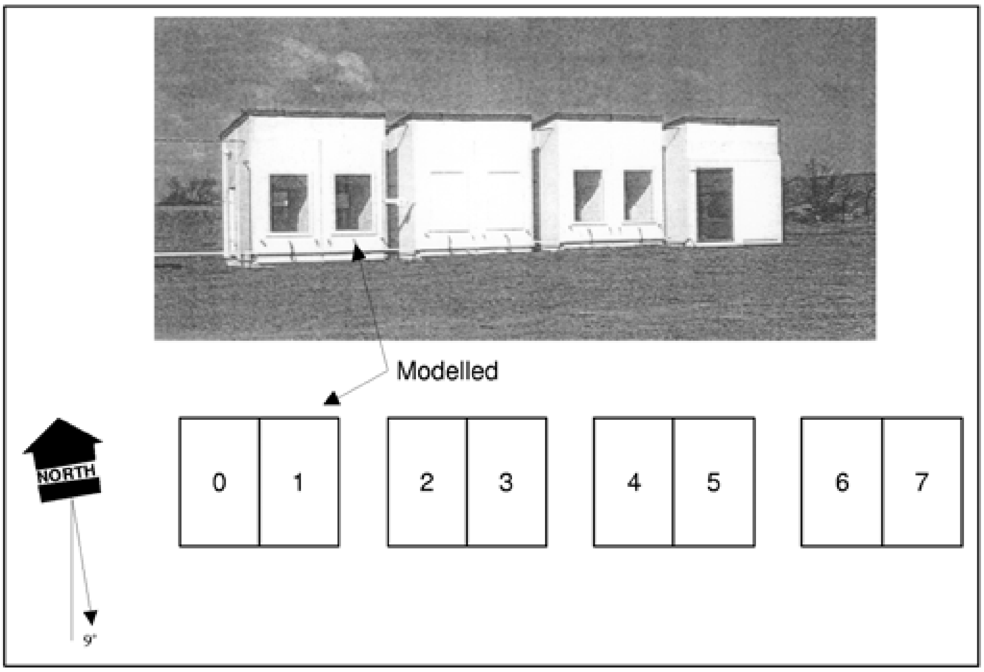


Figure 5.3 Test cell site (Lomas et al. 1994)

5.2.2 BES model

Figure 5.4 shows the BES model that has been used for this study. The geometry and construction is built according to the report without modification, including the small constructions in the edges of the test cells. These small constructions on the edges of the surfaces are hypothetical that were introduced in the descriptions for building model geometry for simulation because of the edge effects. As explained in Lomas et al. 1994 there is an observed heat loss around the edges of the test cell.

The following assumptions were used when creating the model:

- The test cells were developed in pairs. However, the wall connecting the neighbouring cell is heavily insulated. For this reason, only one of the cells is modelled.
- The cell on the other side however is explicitly modelled as it obstructs solar radiation. The BES program uses the sun-tracking algorithm to calculate the solar shading.
- The geometric view factors were calculated using a ray-tracing procedure.
- The default sky model (the Perez anisotropic model) was used to estimate the amount of diffuse solar radiation striking the building surfaces.
- The default insolation algorithm, as used by the BES, was used to calculate the distribution of solar beam radiation to the room’s internal surfaces.
- The fabric thermal property data provided in the IEA report were used unmodified.
- No humidity data were provided in the IEA study for the October heating period, so typical values for England were assumed.

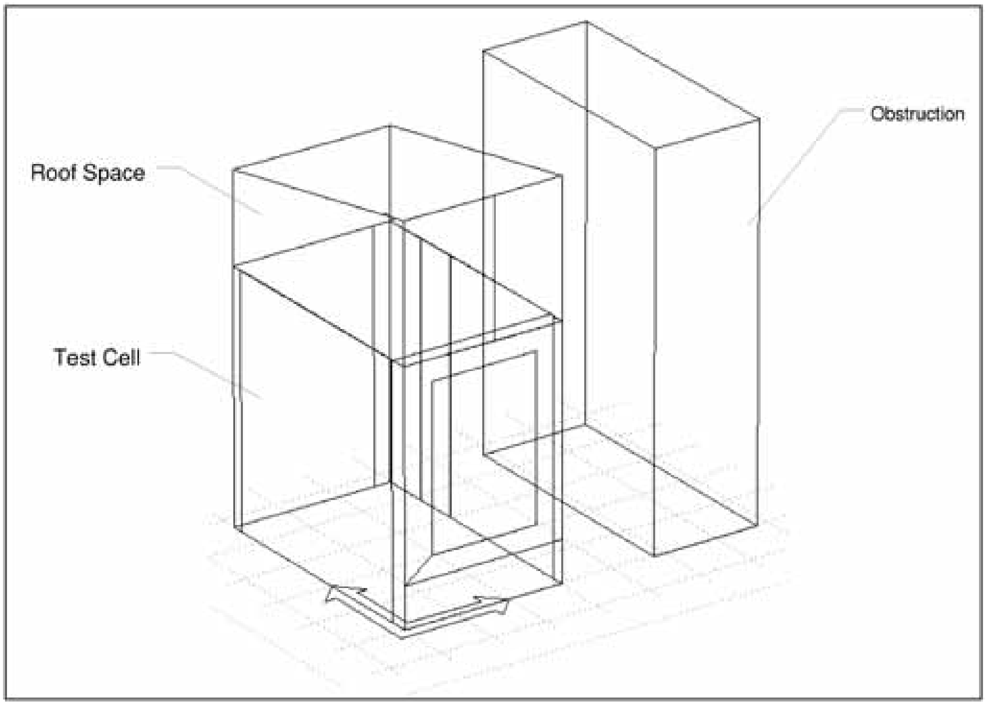


Figure 5.4 BES model

5.2.3 CFD model

Beausoleil-Morrison 2000 in an earlier study used a simplified model for the CFD-coupled simulation (internal). The simplified model did not include the small construction in the corner of the test cell. This simplification was needed because of computer restrictions. Including small construction would need a finer mesh to model, which would result in a longer computation time. With the simplification, the mesh size was 6x9x9.

Because of the difference in the model, the CFD-coupled simulation could not be compared with the uncoupled simulation. Furthermore, the study concluded that the prediction of the convective heat transfer coefficient (CHTC) was not good with the mesh size of 6x9x9. It was suggested that better result would be achieved with a finer mesh.

For that reason, no simplification was attempted for this study. The grid size of 0.1m was required to capture the small construction. This resulted in a mesh size of 15x23x23.

5.2.4 Simulation settings

There are 2 sets of measurement data, each contains 10 days of experiment (however, the first 3 days are considered as a start-up period to minimize the effect of the initial conditions). One set of data is for heating condition (in October) and the other one is for free-floating condition (in May).

Only the heating situation was considered for this study. The (average values) of recorded outdoor conditions are: external temperature of 8.8 °C, global and diffuse horizontal solar radiation of 77 and 32 W/m^2 respectively, and wind speed of 1.6 m/s. The range of daily maximum values for global and diffuse solar radiation are 49 – 412 W/m^2 and 47 – 211 W/m^2.There is no record of relative humidity, so for simulation a typical value for England is used. All climate data (except for relative humidity) used in the simulation were the actual measured data.

Table 5.2 shows a summary of the simulation settings. Setups 1 to 3 were carried out for calibration purpose to establish confidence in both the geometry definition and the coupling mechanism. Based on the result of these 3 setups, some modifications were introduced, and the last two setups were simulated using the modified mechanism.

Table 5.2 Summary of simulation settings

	CHTC definition on internal surfaces	Gopher run	Turbulence model (final CFD run)
Setup 1 (base case)	Alamdari-Hammond (1983) correlation	n.a.	n.a.
Setup 2	Heater off: • Alamdari-Hammond (1983) correlation Heater on: • Wall: Khalifa and Marshal (1990) correlation • Floor: Alamdari-Hammond (1983) correlation	n.a.	n.a.
Setup 3	Internal coupling	yes	Standard k-e
Setup 4	Internal coupling	no	Indoor Zero Equation
Setup 5	External coupling	no	Indoor Zero Equation

The room was heated during the day from 06:00 to 18:00. The heater was modelled as a heat source with the same maximum heat output as in the experiment. The heat output was divided, as estimated in the report (Lomas et al. 1994), in a ratio 40:60 for convection and radiation. In the experiment, a PID controller was used for the heater. The simulation, however, uses an ideal controller to inject the heat directly into the room.

The test rooms were tightly sealed and the experiment was conducted with zero air infiltration assumption. This was also assumed for the simulation.

The simulation time step is 15 minutes. For CFD-coupled simulations, CFD was invoked only on the last day when the heater was on (i.e. from 06:00 to 18:00 on 26-Oct). The CFD simulations, both for internal coupling and external coupling, used the same convergence criteria (i.e. 10-6 residuals error for energy and 10-3 for others). The iteration for CFD simulations were limited to 500 iterations, and the iteration always starts from the latest data from the previous timestep.

5.2.5 Calibration

The calibration procedure has two objectives, namely (1) to ensure that all parts of the experiment are modelled correctly, and (2) to evaluate the current capabilities of internal coupling mechanism (as described earlier in Section 4.3), in the perspective of using this mechanism for external coupling. Setups 1 – 3 are used for this purpose.

Figure 5.5 shows the room temperature fluctuations for 7 days. The predicted temperature can follow the fluctuations. The temperature decay is particularly accurate with the maximum error of less than 2 °C occurred when the temperature started to rise again. The simulation predicted a faster rate of temperature rise due to the assumption of ideal controller used in the simulation.

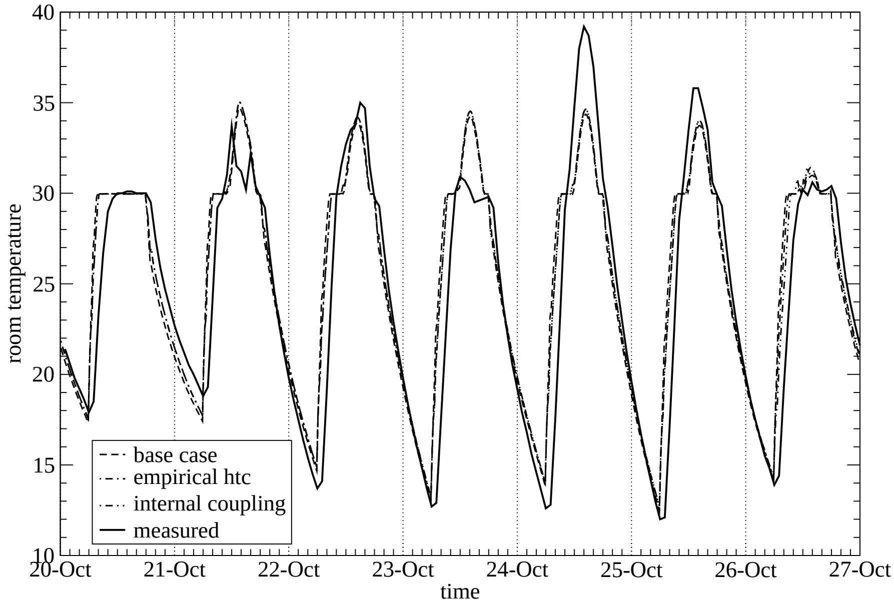


Figure 5.5 Room temperature (20-Oct to 26-Oct)

However, there are big differences for a few hours in the afternoon from day 2 to day 5. During this period, the simulated room temperature has a similar pattern, regardless the pattern of the measurement result. The following are the possible causes for this discrepancy in the room temperature:

- These are the time steps where the solar radiation was very high. The BES result is known to be sensitive to the definition of the sky model. The current problem could be caused by the default sky model (the Perez anisotropic model), that was used to estimate the amount of diffuse solar radiation striking the building surfaces, and its insolation algorithm (that was used to calculate the distribution of solar beam radiation to the room's internal surfaces).
- The measurement error which was estimated around 20% (of absolute temperature). Furthermore, the measurement points were not specified. The air temperature was recorded at three heights (low, middle, high) without any further details on the exact location. The air temperature data presented here is from the middle point.

To avoid the above problem further detailed discussion will focus on the day where solar radiation is not high, i.e. the last day of the experiment (26-Oct). As can be seen in Figure 5.6, the temperature prediction is very close. The difference occurred when the heater is on (at 06.00) and when the heater is off (18:00). The temperature reached the steady state value within 2 or 3 hours in the simulation, while in the experiment it took 5 hours. This is solely attributed to the ideal controller that is used in the simulation, as opposed to much slower PID controller as used in the experiment.

Figure 5.7 shows the energy consumption for the whole period of simulation. The base case result (67.9 MJ) is similar to the previous result that was derived with an earlier version of BES as reported in Lomas et al (1994). This gives confidence in the current model.

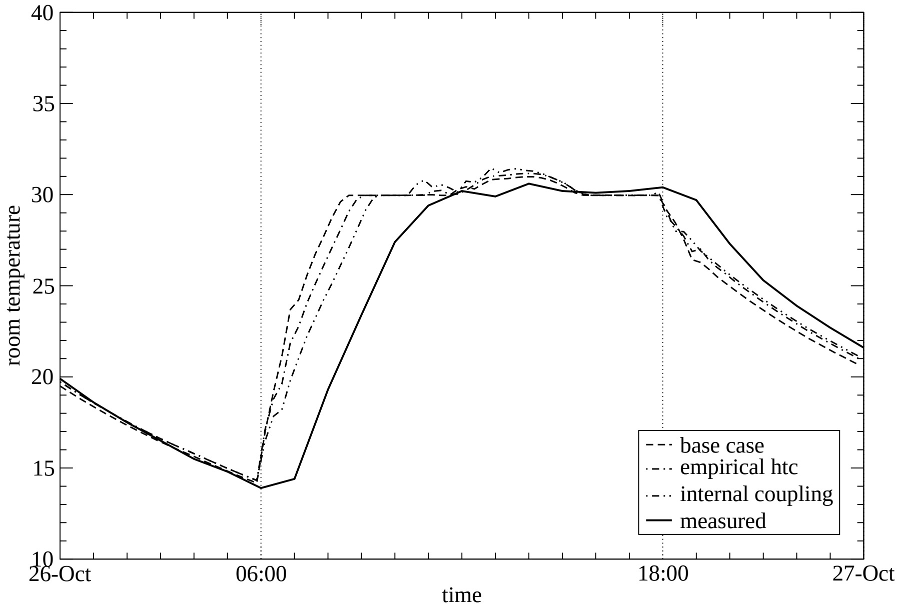


Figure 5.6 Room temperature (26-Oct)

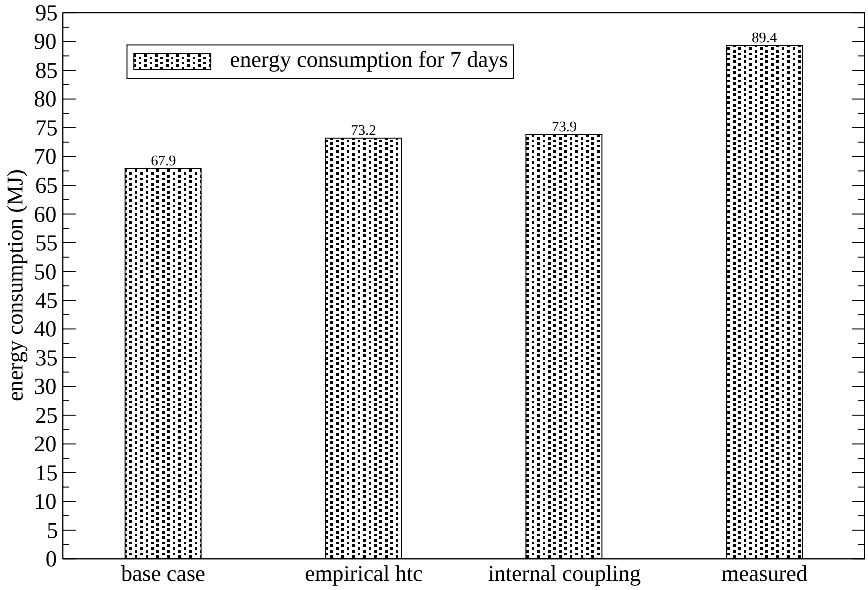


Figure 5.7 Energy consumption (20-Oct to 26-Oct)

Applying an empirical specification of CHTC results in higher energy consumption, increasing around 5%. This is attributed to the higher CHTC during the time when the heater is on, around 10 W/m^2K compared to around 3 W/m^2K for the base case (Figure 5.8).

The effect of applying a CFD-coupled simulation is significant in terms of energy consumption prediction. Figure 5.9 shows the energy consumption for one day (as coupled simulation is carried out only for this day). Using empirical CHTC increases the energy prediction by 8% compared to the base case, while using internal coupling results in a 15% increase.

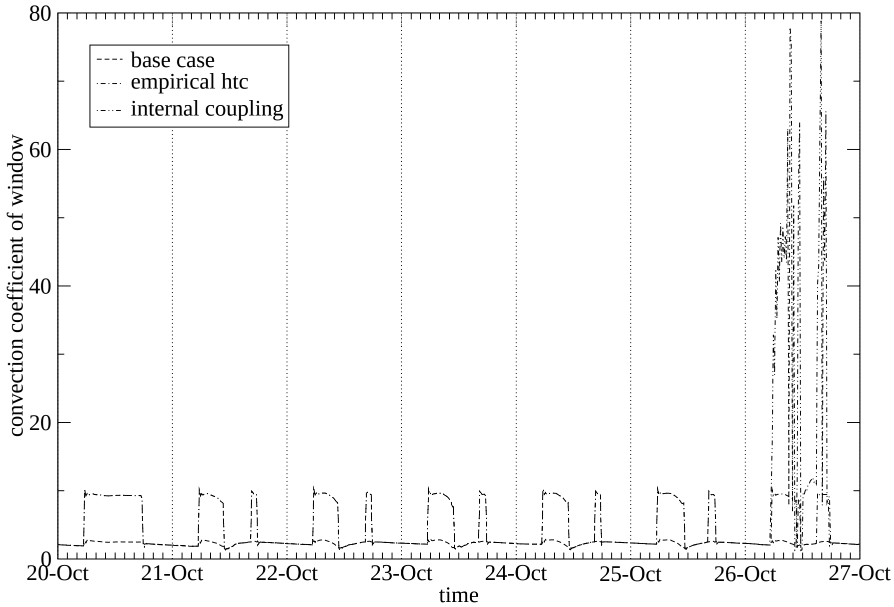


Figure 5.8 CHTC of window (20-Oct to 26-Oct)

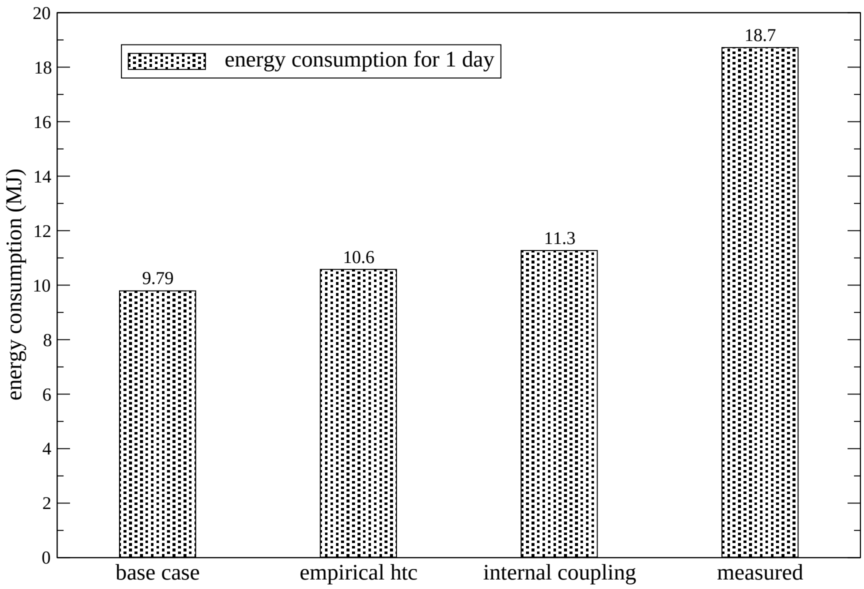


Figure 5.9 Energy consumption (26-Oct)

However, the predicted values are still far too low compared to the measured value even if the error band is considered (18.7 ± 3.74).The large discrepancy between the simulation and measurement values could be due to the efficiency of the radiator, which is not reported. It should be noted that the simulation results represent the energy demand, while the measurement represent the energy consumption, which already includes the efficiency of the heating and electrical system.

The significant increase in the energy consumption prediction is caused by a very high CHTC (up to 80 W/m^{2}K, as shown in Figure 5.10) which is not realistic for this type of flow.

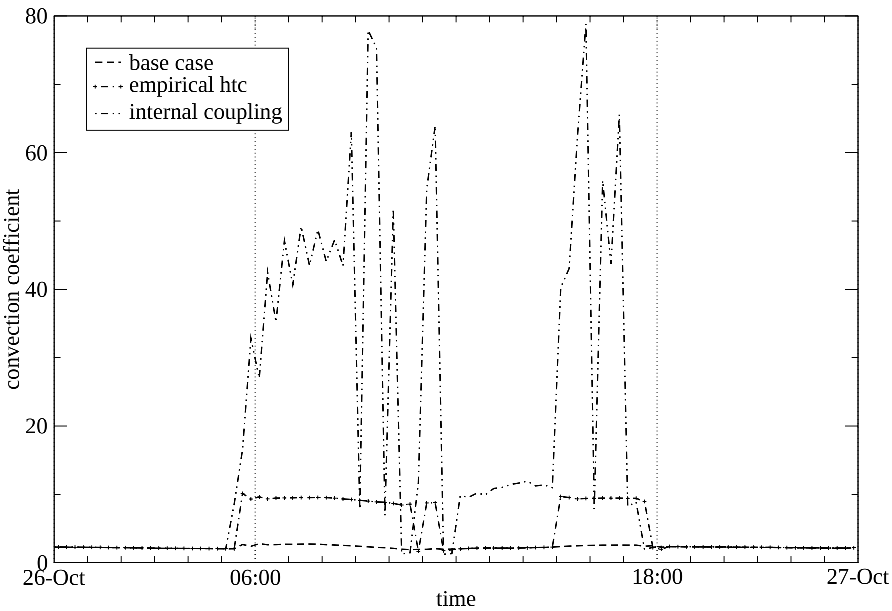


Figure 5.10 CHTC of window (26-Oct)

The internal coupling case (Setup 3) was carried out using the existing mechanism available in ESP-r. The CHTC for the internal surfaces were calculated initially by empirical correlations (as in Setup 2). During the times where the CFD is invoked, the CHTC can be updated via the CFD result. For Case 3 the applied criteria for that was:

$$0.1\ CHTC_{empirical} < CHTC_{CFD} < 10\ CHTC_{empirical}$$

to accept or reject the CFD prediction of CHTC. The empirical CHTC was around 15 W/m^{2}K for this investigated flow field. The loose criteria therefore would accept any values between 1.5 to 150 W/m^{2}K. If the $CHTC_{CFD}$ was rejected, the thermal domain calculation used the empirical value for further calculation.

The (full) CFD simulation uses different simulation settings (turbulence model, wall function, etc) as determined by the investigative CFD simulation. For Setup 3 however, standard k-ε turbulence model with log-law wall function was always selected by the coupling mechanism. Beausoleil-Morrison (2000) found that most of $CHTC_{CFD}$ were rejected because they were too high compared to the empirical values. He assumed that the high value was caused by the use of the standard k-ε turbulence model in combination with the log-law on a very coarse grid, so that the conditions for application of the log-law could not be met.

In this study a finer mesh (15x23x23 compared to 6x9x9 used by Beausoleil-Morrison 2000) was applied. However, it still was concluded that the $CHTC_{CFD}$ prediction was too high. The values were accepted by the thermal domain simply because of the loose criteria. With stricter criteria (as proposed by Beausoleil-Morrison 2000), i.e.:

$$0.2\ CHTC_{empirical} < CHTC_{CFD} < 5\ CHTC_{empirical}$$

the values would have been rejected. The grid size adjacent to the wall is regarded as the cause for the poor performance of the turbulence model. Yuan (1995) found that the turbulence model is sensitive to the size of the first cell adjacent to the wall. In this study a uniform grid size of 100mm was applied, while Yuan (1995) found that accurate results would require a much smaller size of the first grid cell (in the order of 5mm).

The conclusion from this calibration study is that the 15x23x23 mesh is still too coarse for standard k-ε with log-law to resolve reasonable values of $CHTC_{CFD}$. Using a finer mesh is not an option as it will lead to more computation time. The other option is to use another turbulence model that can produce a reasonably good result with a coarse mesh.

Furthermore, the 15x23x23 mesh is too fine for the investigative CFD simulation. Beausoleil-Morrison (2000) reported that the investigative CFD simulation uses only a small fraction (5%) of the computing time. However, that study used a very coarse mesh (6x9x9), so the overall computing time is not high. Setup 3 took 27h51m to finish with a mesh size of 15x23x23. The same case simulated using a coarser mesh (6x9x9) took only 1h14m to finish. If the investigative CFD simulation is by-passed, the simulation time can be reduced significantly.

The above considerations are used to modify the coupling mechanism. The following are the changes:

1. The mechanism will bypass the investigative CFD simulation (the gopher run), so there is only one CFD simulation for every CFD invocation.
2. The zero-equation turbulence model is used.

The above changes have been implemented as explained earlier in Section 4.4. The simulations in the following sections were performed using this new mechanism.

5.2.6 Validation of external coupling

5.2.6.1 Simulation settings

In this section the results of Setups 1, 2, 4 and 5 will be compared. The CFD-coupled simulations use the updated mechanism as described in the previous section.

Internal coupling uses the co-operative definition of CHTC (as explained in Section 4.3.3). External coupling, on the other hand, will use the Reynolds analogy for the definition of CHTC and passes only the CHTC values to the thermal domain. A comparison will be made in the difference between using the CHTC and $CHTC_{nom}$ as defined earlier in Chapter 4.

5.2.6.2 Room air temperature

Figure 5.11 shows the room temperature for 1 day. The result is similar with Figure 5.6. Even though the rise time of the simulation is relatively faster then the experimental result, there is a noticeable difference between the 4 simulation cases. The base case rises the fastest, while the others tend to lag behind, in the order of the CHTC values. The higher the CHTC values in general, the slower the air-point temperature rises. External coupling shows the slowest response. However, it is still much too fast compared to the experiment due to the difference in the heater controller setting.

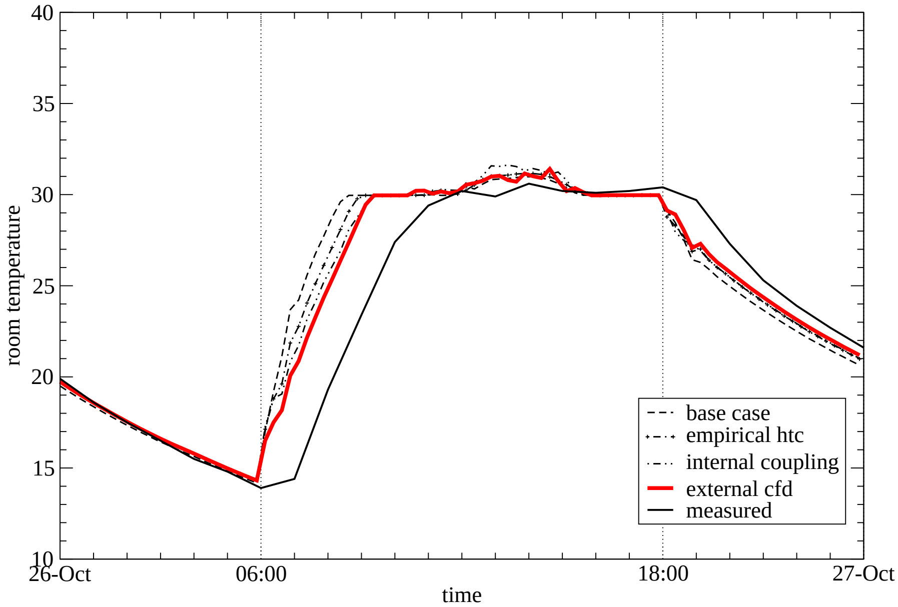


Figure 5.11 Room temperature (26-Oct)

5.2.6.3 CHTC

Figure 5.12 shows the CHTC for the window. Most of the time, the internal coupling (Setup 4) result shows exactly the same values with the empirical values (Setup 2). This means that the prediction of CHTC from CFD is larger than 5 times the empirical value so that it was rejected. In that case the thermal domain used the empirical value instead of CFD-predicted value. How high the CFD-predicted values reach can be seen in the values around 06:00hrs, where they fall within the acceptance criteria. Nevertheless, they are still too high (more than 40 W/m^{2}K) for this type of flow. The external coupling simulation (Setup 5), on the other hand shows, consistently similar values for the CHTC (around 10 – 14 W/m^{2}K), which is higher then the values calculated by empirical correlations.

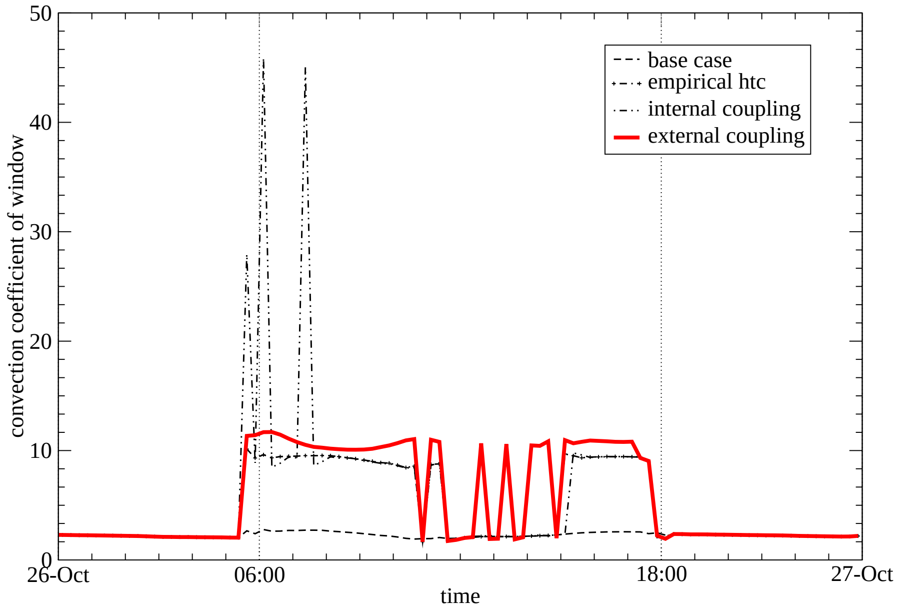


Figure 5.12 CHTC of window (26-Oct)

For a few hours after mid-day, the empirical correlation gives the same values as the base case. The reason is that during this time, the heater controller switched the heater off, so the empirical correlation used the same correlation as the base case. The external coupling managed to follow this trend for a few time steps, but failed in some other time steps. The reason for this is that the external CFD program did not know the operation status of the heater, and simply assumes that the heater is on every time it is invoked. This is a bug in the source code and this bug has been corrected.

5.2.6.4 The effect of using CHTCnominal

Figure 5.13 shows the $CHTC_{nom}$ values compared to CHTC values calculated by other methods. The difference between $CHTC_{nom}$ and external coupling prediction shows that there is a significant temperature non-uniformity in the room. The $CHTC_{nom}$ ensures that the convective heat calculated by BES is the same with the CFD prediction.

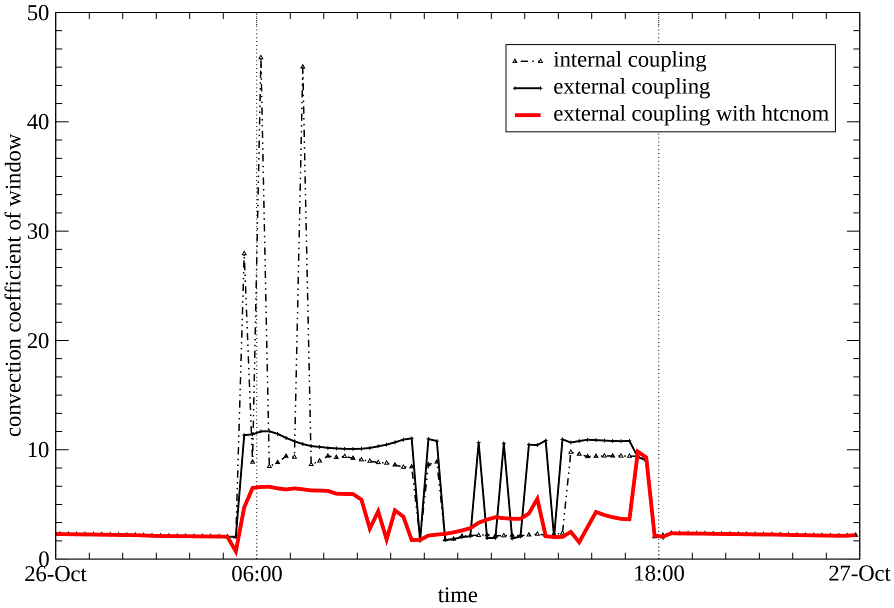


Figure 5.13 Comparison of CHTC values between coupled simulations

There is no significant difference in the air temperature prediction, as shown in Figure 5.14. The effect can be best seen in the energy prediction as discussed below

Figure 5.15 shows the prediction of energy demand for all simulations. Using empirical CHTC increases the energy prediction by 8% compared to the base case, while using internal coupling results in a 15% increase.

External coupling (without $CHTC_{nom}$) slightly increases the energy demand compared to the internal coupling. Applying the $CHTC_{nom}$, however, causes the energy demand prediction to a level similar to the prediction using empirical CHTC. This is because without using $CHTC_{nom}$, BES uses the over-predicted value of CHTC.

As discussed earlier, the predicted values are still far too low compared to the measured value even if the error band is considered (18.7 ± 3.74). It should be noted that the simulation results represent the energy demand, while the measurement represent the energy consumption, which already includes the efficiency of the heating and electrical system. The large discrepancy between the simulation and measurement values could be due to the efficiency of the radiator, which is not reported in the experimental report.

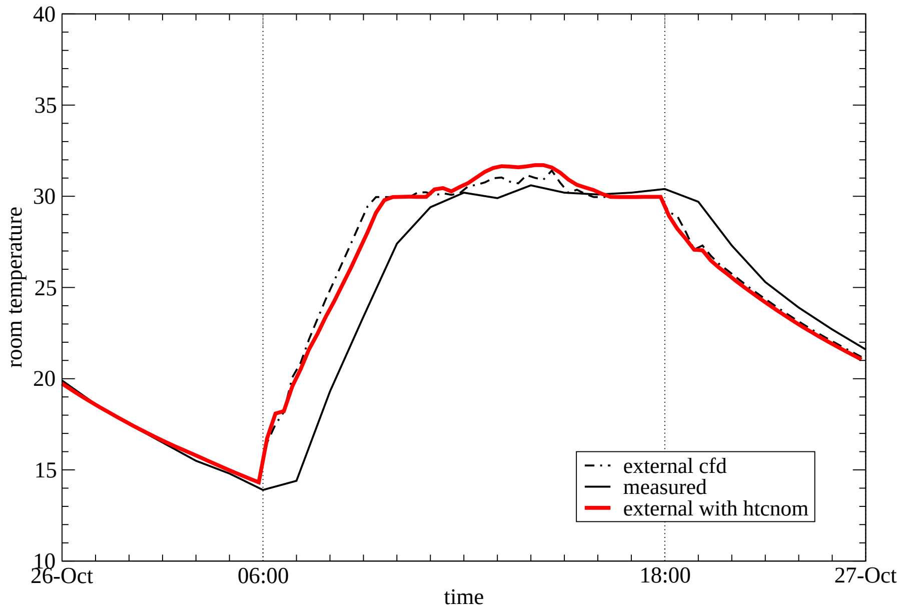


Figure 5.14 Effect of using $CHTC_{nom}$ on air temperature

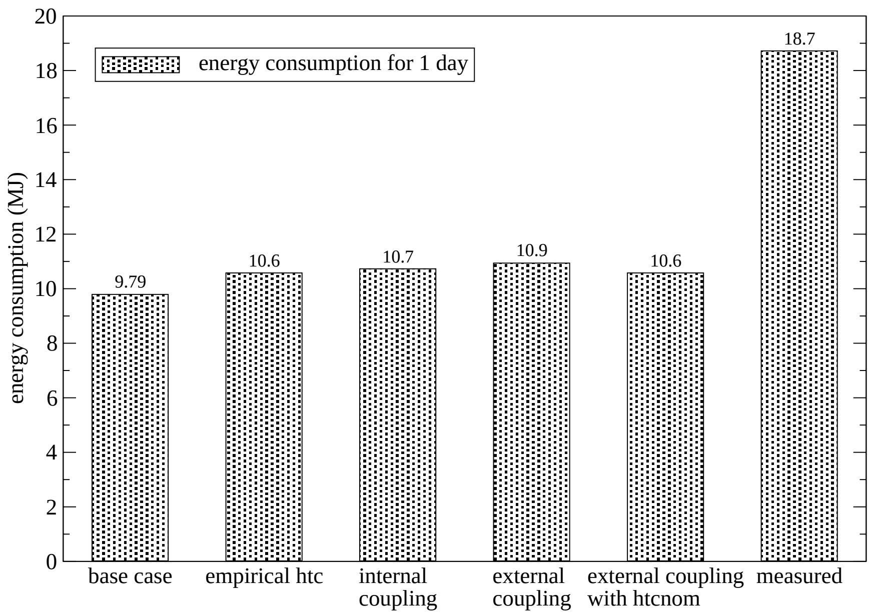


Figure 5.15 Comparing energy consumption including the effect of using $CHTC_{nom}$

5.2.6.5 Computing time

Table 5.3 shows the computing time for the performed CFD-coupled simulations. Considering the prediction of CHTC and comparing with the time required to achieve the result, external coupling shows a clear advantage over the internal coupling It is unclear why the internal solver performed so badly in this case.

Table 5.3 Comparison of computing time for CFD-coupled simulation

Case	Summary	Time (hr:min:sec)
Setup 3	Internal coupling with gopher run	27:51:46.6
Setup 4	Internal coupling without gopher run	10:32:57.2
Setup 5	External coupling without gopher run	00:23:56.0

5.3 Case 2: IEA Annex 26 Atrium – natural convection

5.3.1 Case descriptions

The atrium (Figure 5.16) is located in Yokohama, Japan, and has been studied extensively to produce high quality data for the validation of simulations of large spaces, as part of a research program coordinated by IEA Annex 26 (Heiselberg et al. 1998). Many simulation studies have used these sets of data for validation purposes.

The atrium is facing south and has three glass walls (south, east, and west), a glass roof, and two insulated surfaces (north wall and floor). Figure 5.17 shows the dimensions of the atrium. The full description of the atrium and the experimental settings can be found in Heiselberg et al. 1998, Hiramatsu et al. 1996, and Ozeki et al. 1996.

The selected setting for this study was denoted in the reports as Case 2(a). For this case, the north wall and the floor were painted white. The measurement was carried out without any ventilation and air conditioning on a spring day (31-Mar-1994). The measurement setting, methodology and results are well-documented and can be found in Murakami et al. 1994.

Figure 5.16 IEA Annex 26 Atrium (Yokohama, Japan)

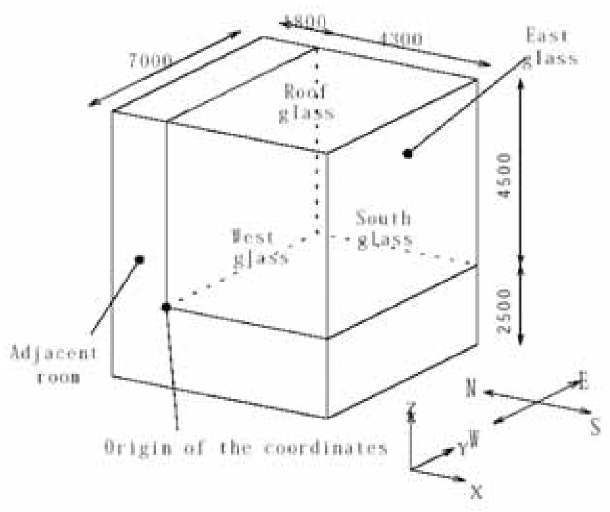


Figure 5.17 Dimension of the atrium

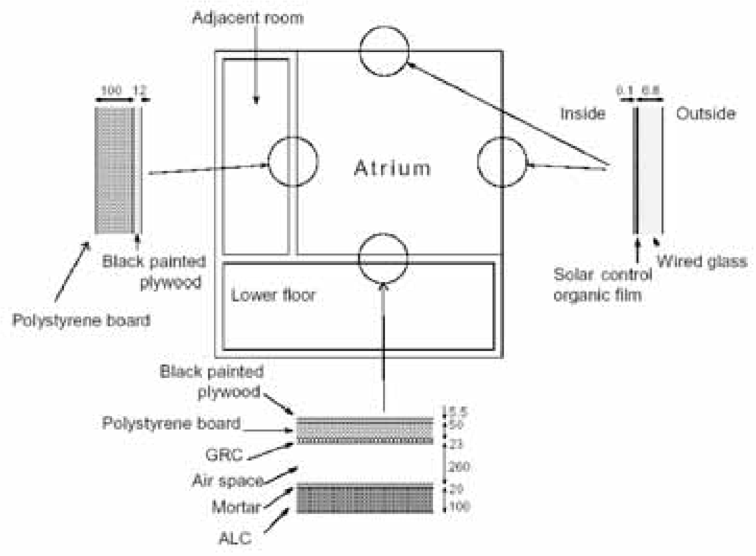


Figure 5.18 Construction elements of the atrium

5.3.1.1 BES model

For this study, two models were created (Figure 5.19.a and Figure 5.19.b). Model A is the simplified model of the atrium where the steel frames are left out. Schild (1997) found that the heat transfer through the frames are very significant so that it should not be left out. For this reason, Model B was developed to include the frame. The consideration for modeling the frame as shown in Figure 5.19.b is discussed in calibration section below.

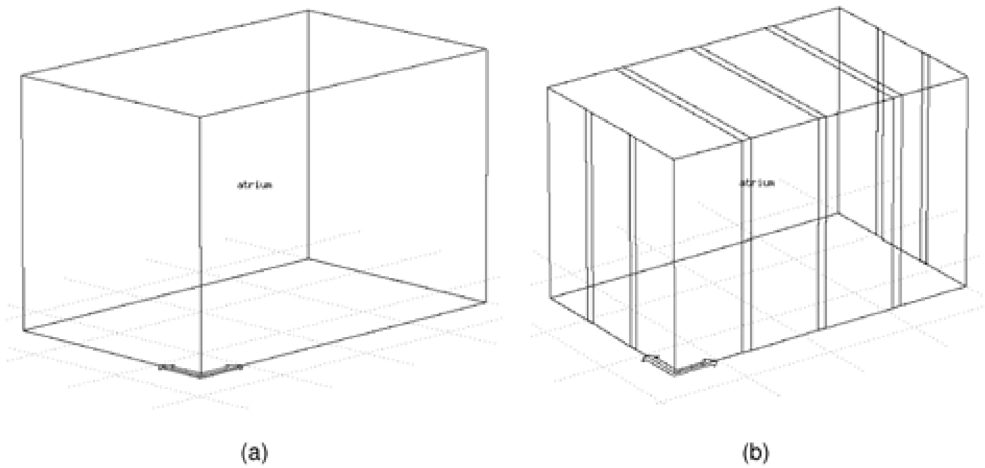


Figure 5.19 IEA Test Room geometry

5.3.2 CFD Model

For Model A, a coarse mesh of 10x10x10 was created for internal coupling. The coarse mesh was intentional due to the limitation of the solver which would take much longer time to calculate models with finer mesh. For Model B, however, a finer mesh was used due to the geometrical demand to include the frame. The resulting mesh was 19x14x14.

The CFD geometry for external coupling, on the other hand, uses a finer mesh, uniform grid size of 0.2m, for both Model A and Model B. The resulting mesh was 35x23x23.

5.3.3 Simulation settings

The experiment report has estimated the leakage from the glazed structure as 9 cm^2/m^2 floor area. With this value, the experiment can assume air-tight condition. The simulations were also carried out with zero infiltration rates.

The simulations were carried out for 24 hours with a time-step of 15 minutes. CFD simulation was invoked every time step, so that in total there were 96 steady-state CFD simulations for every coupled case.

There were six cases studied, three cases for each geometrical model. The uncoupled cases were simulated using ESP-r without CFD coupling. The CHTC for this case was calculated using the Alamdari-Hammond correlation. These two cases are considered the base case. Table 5.4 shows the settings of the cases.

5.3.4 Calibration

The steel frame is actually very complex to model. Apart from the external frame (which holds the glass), there is an internal frame which holds the overall structure of the atrium. The geometry of the frames was not modeled as in reality, because it would lead to a very complex model for the CFD simulation. Below are some considerations in developing Model B:

1. The total frame area from the outside surface is kept similar (around 10% of the glazed area which means around $10m^2$).
2. The simplest way to model the frame is introducing rectangular sections into the surfaces. If the width of the rectangular sections is taken as 0.2m, with the

length of 4.5m, the number of sections needed is 11. Using geometrical manipulation, only 10 of these sections will be used so that the geometry can have a simple CFD mesh. The south surface and the ceiling will have 3 sections each, and the east and west surfaces will have 2 sections each. Calculating back, the surface area of the frame (viewed from outside) is (4.5x0.2x7) + (4.3x0.2x3) = 8.88 m^2.

3. To capture the thermal capacity of the frame, the total volume is also kept similar to the reality. From the report, the estimated volume of the frame is 0.46 m^3. Taking the total area of the frame is around 10m^2, the modelled frame should have a thickness of 0.046m.

Table 5.4 Simulation settings and time

Model	CFD	Mesh	Time
Model A	No CFD	n.a.	0:01:50
Model A	Internal coupling	10x10x10	1:33:23
Model A	External coupling	35x23x23	13:17:31
Model B	No CFD	n.a.	0:03:53
Model B	Internal coupling	19x14x14	7:13:45
Model B	External coupling	35x23x23	10:30:32

The above considerations results in a similar frame area viewed from outside, which is important for insolation calculation. However, the report estimated that the total surface area of the frame viewed from inside is 72m^2, which is important in the convection calculation. The modelled frame has only 8.88 m^2 frame surface area which is far too low. However, no further refinement in this direction is attempted to keep the CFD model simple.

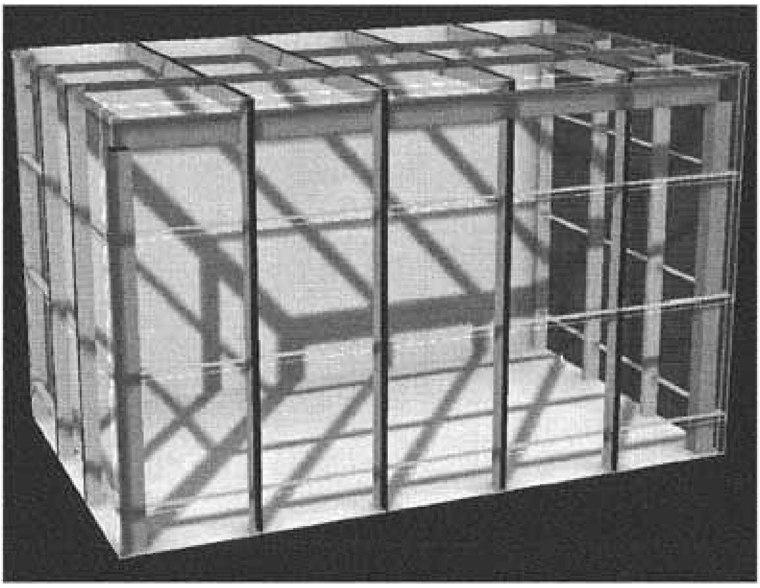


Figure 5.20 The steel frames (Schild 1997)

Apart from the shape of the steel frame, the specification of the steel properties brings in another level of difficulty. The properties of the steel frame are not specified in the report. Furthermore, the standard steel properties as provided in the BES program could not obtain the correct temperature rise during the simulation compared to the measured value.

Optical property of the glass also brings uncertainty. The glass has different optical property depending on the incidence side, i.e. the radiation going inside out and outside in will have different reflected, absorbed and transmitted values. It is not possible to model such detail in the simulation. The optical property used in the simulation was at least consistent with the material properties of the glass and the film coating.

Some simulations were run to try several material and optical properties, and after a few cycles of trial-and-error, the simulation settings can give good results compared to the measured data.

5.3.5 Results and discussion

5.3.5.1 Computation

The CFD coupled simulation, both internal coupling and external coupling, used the zero equation model. Both also used the same convergence criteria (i.e. 10^{-6} residuals error for energy and 10^{-3} for others). The iteration for CFD simulations were limited to 500 iterations, and the iteration always starts from the latest data from the previous time step.

As pointed out earlier, the meshes of the internal coupling cases were intentionally made coarser due to the solver limitations. On the simple model, with a mesh of 10x10x10, internal coupling case took 1 hr 15 min to run. When the mesh was refined, due to the geometrical demand to include the frame, to 19x14x14 (less then double), the computing time became more than 4 hrs (almost four times). The external coupling, on the other hand, can use a finer mesh (uniform grid size of 0.2m) with a more or less similar computing time. See Table 5.4.

External coupling, on the other hand, can have up to twice finer CFD mesh with comparable computing time. However, this conclusion is very much dependent on the choice of the solver. The important point here is that external coupling offers a freedom to choose the most powerful solver without the need of much coding work.

5.3.5.2 Air temperature

Figure 5.21 and Figure 5.22 show the comparison between the measurement and simulation results of the air temperature. The measured air temperature is an average value from 27 measurement points. For this measurement setting, such averaging is valid as the temperature can be considered uniform.

Both the simulations for Models A and B underestimated the air temperature. Model A shows a slight sensitivity towards the CHTC, where the peak air temperature decreased when the coupled simulation was used. Internal coupling reduced the peak temperature 2 °C, while with external coupling the peak temperature decreased 4 °C. However, the coupled simulation results were less accurate compared to the uncoupled simulation.

Model B however shows that it is not sensitive towards the CHTC. The uncoupled and coupled simulation results were close to each other. All of them have the peak air temperature of 4 °C less than the measured data.

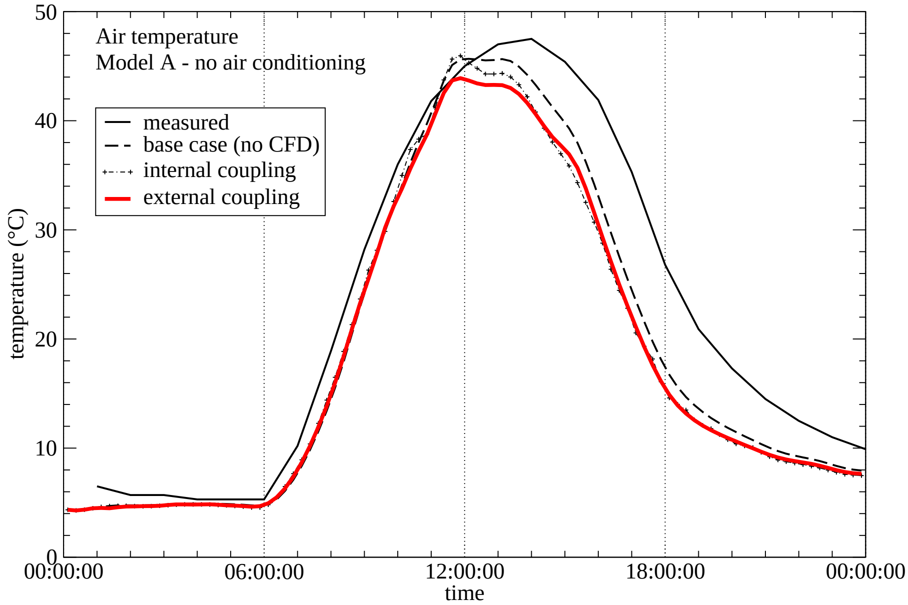


Figure 5.21 Air temperature comparison (Model A)

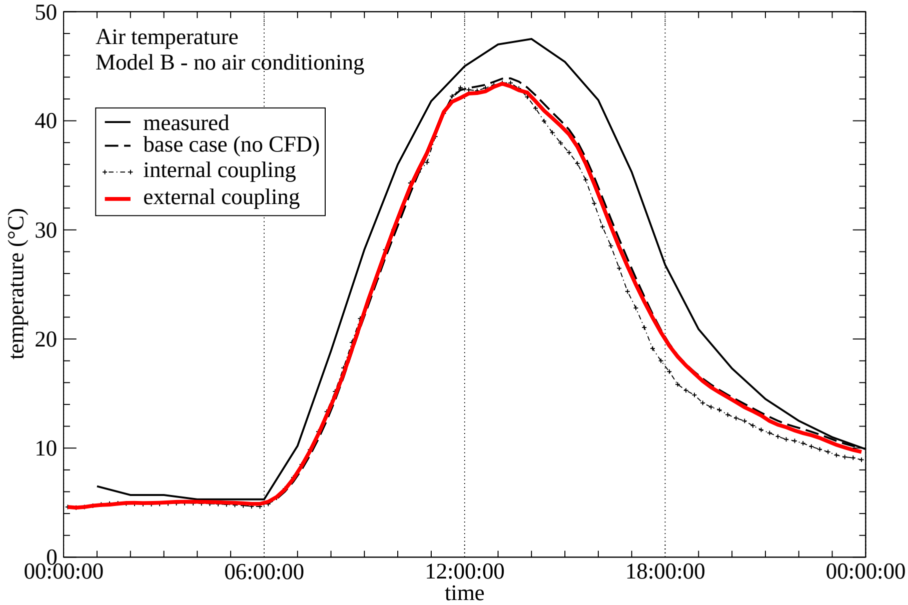


Figure 5.22 Air temperature comparison (Model B)

5.3.5.3 Wall temperature

Figure 5.23 and Figure 5.24 shows the internal surface temperature for Models A and B. The predictions show reasonable agreement with the measurement data. The ceiling and the east surface temperature are not sensitive towards the CHTC where the uncoupled predictions were relatively the same as the coupled simulation predictions. For other surfaces, the coupled simulation prediction has better accuracy compared to the uncoupled simulation.

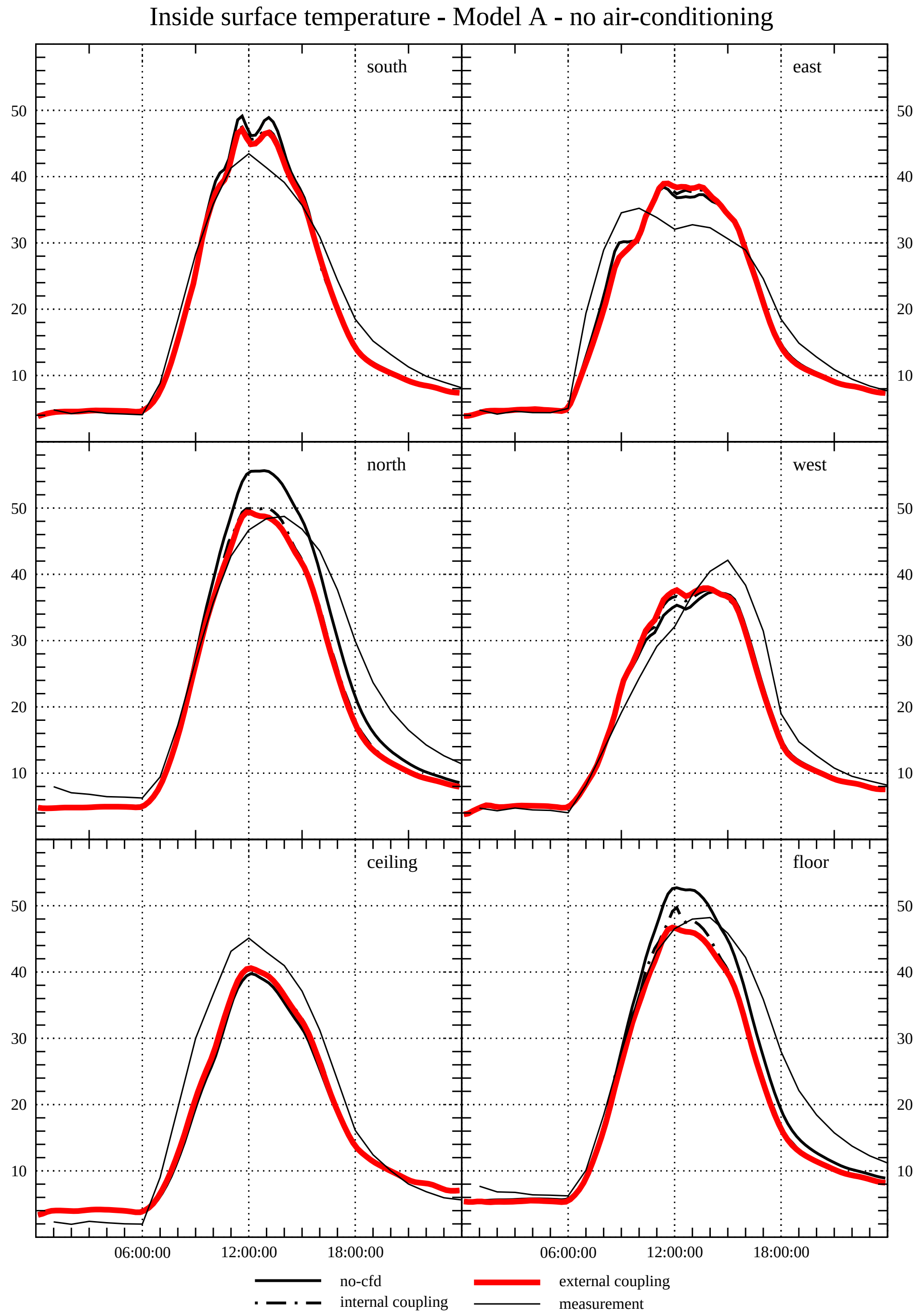


Figure 5.23 Inside surface temperature (Model A)

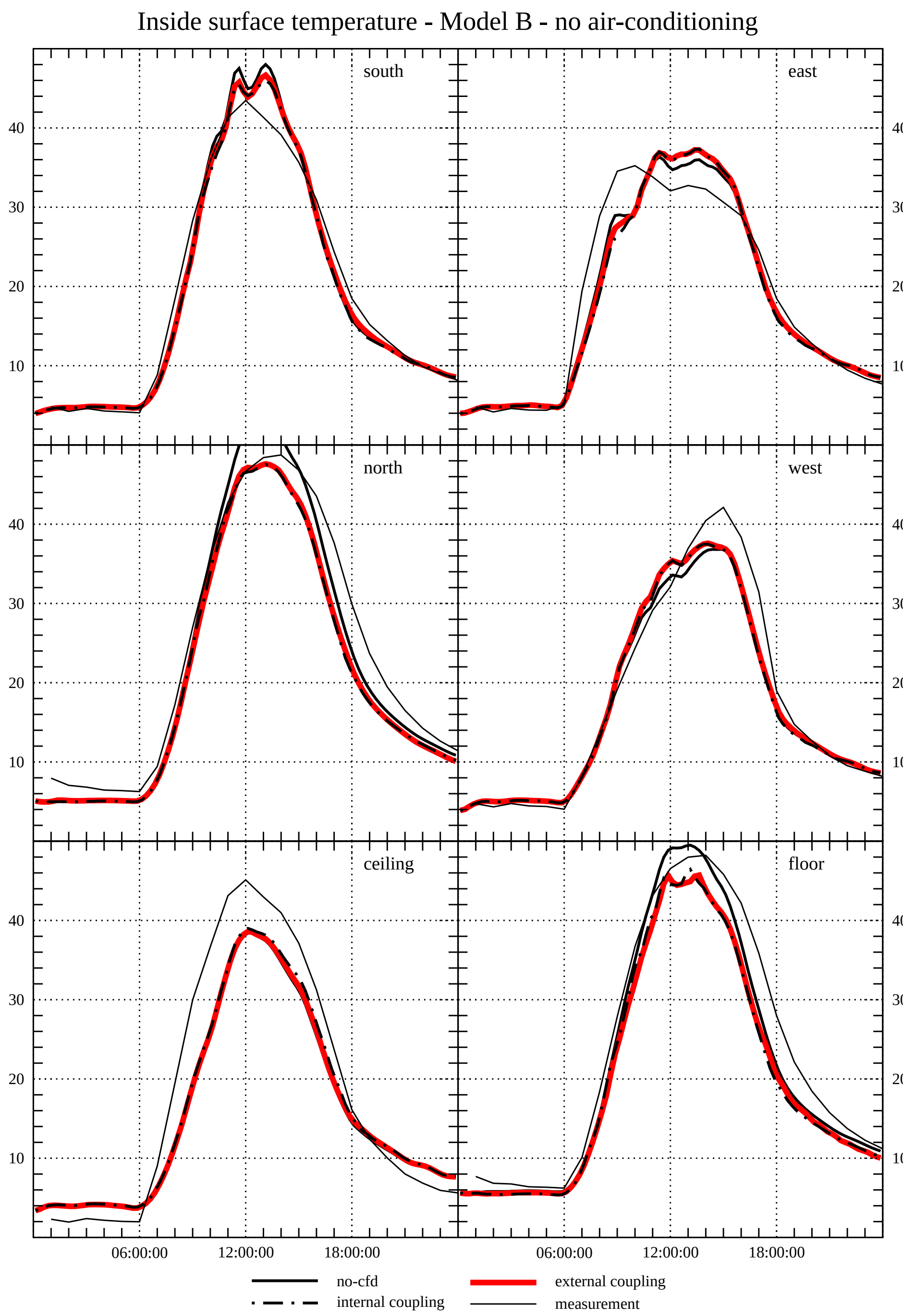


Figure 5.24 Inside surface temperature (Model B)

5.3.5.4 CHTC

Figure 5.25 shows the comparison of CHTC values for Model A. The fluctuation in the coupled simulation result (both internal and external coupling) actually shows the coupling controller in action.

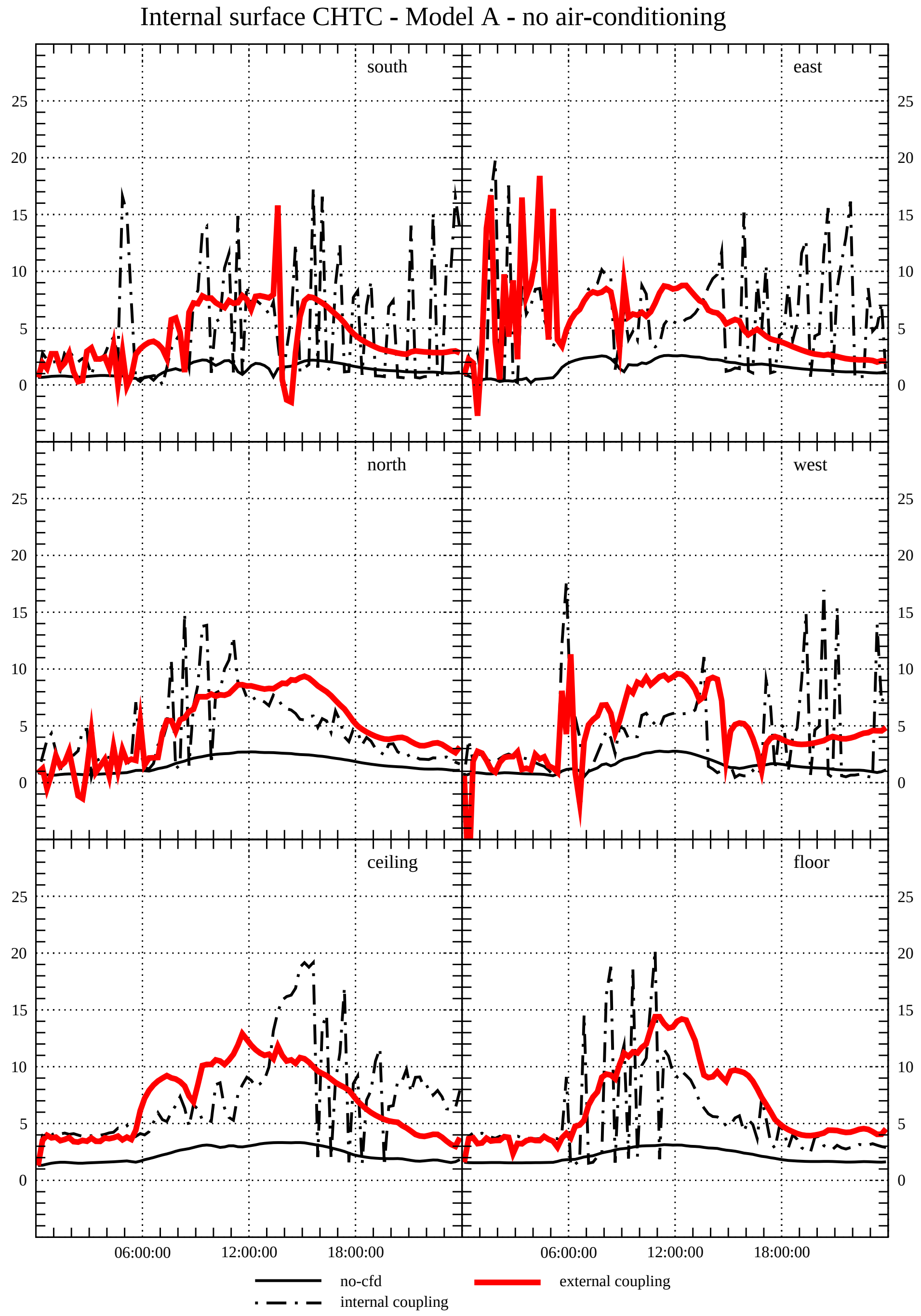


Figure 5.25 CHTC (Model A)

In general, the CFD-coupled simulations predict a higher value of CHTC. However, the coupling controller will check the CHTC value to ensure that it falls within an acceptable range (not too high and not too low). When the value from CFD is out of the acceptable range, the CHTC will be rejected, and the thermal domain will use its own CHTC value based on empirical correlations. This rejection is shown in the graph when the CHTC-value falls down to the base case (no-CFD) value.

The CHTC value of the internal coupling case fluctuates more often compared to the external coupling case. This means that the predictions of CHTC by the internal coupling simulation were rejected more frequently. As shown in Figure 5.25, the values could reach up to 15 W/m^{2}K, above which many of the values were rejected. On the other hand, the CHTC predictions by external coupling were rejected less frequently.

Figure 5.26 shows CHTC values Model B. The values shown in the graph are the average values of glass section of the walls. The same trend as the result of Model A can be observed from Figure 5.26.

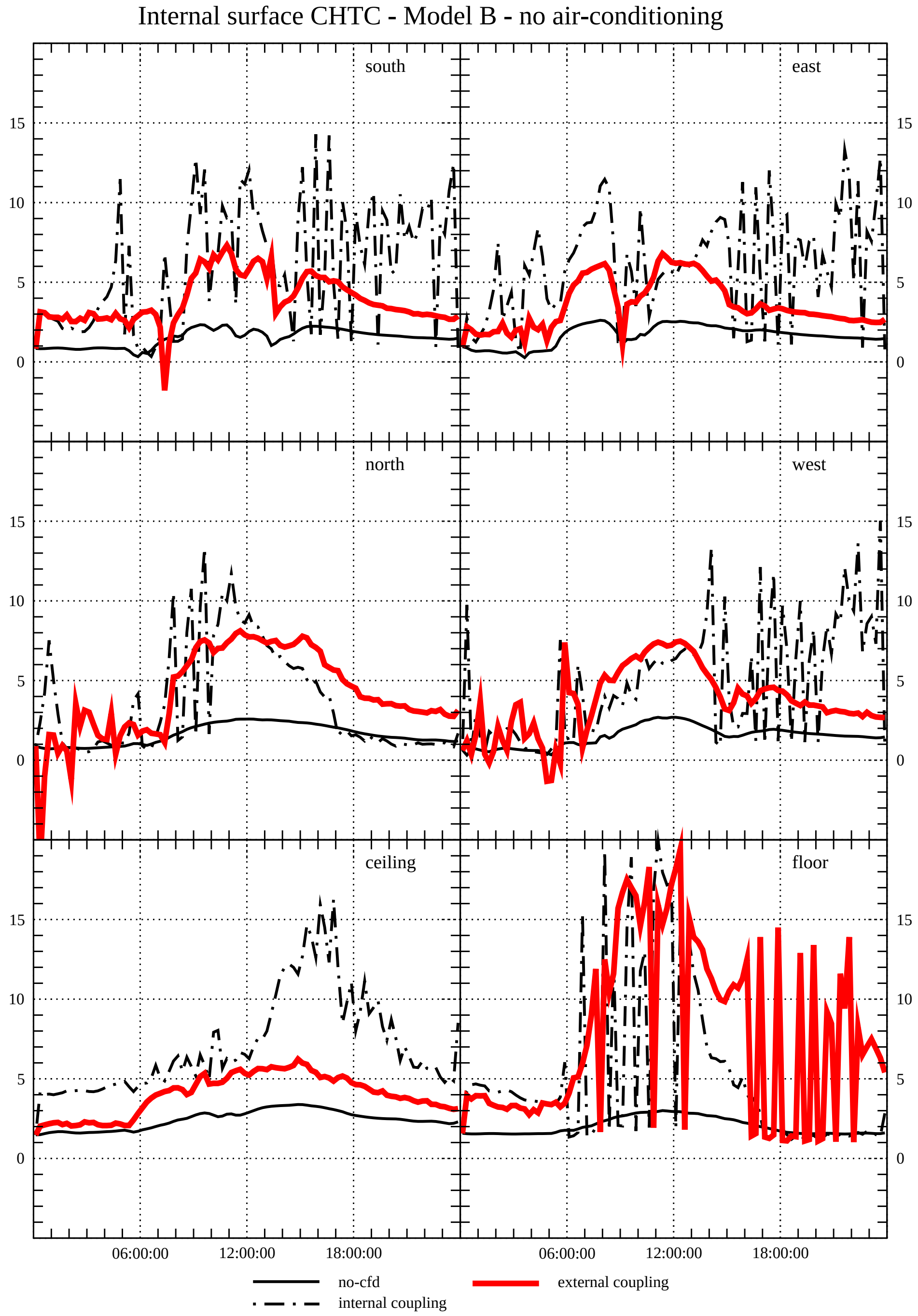


Figure 5.26 CHTC (Model B)

There is no measurement result that can be used to validate the CHTC result. Hiramatsu et. al (1996), however, have used Wilke's correlation to estimate the heat flux from the walls. This results in an estimated range of CHTC values between 3.6 – 4.1 W/m^2K.

5.3.5.5 Convective heat

Figure 5.27 and Figure 5.28 show the convective heat rate on the inside surface of all walls. On the model with frame, the values are the sum of the values for the separate parts of the south wall. As expected (based on the CHTC predictions) the coupled simulation enhances the heat flow at the surface. It is consistently higher (either loss or gain) than the base case.

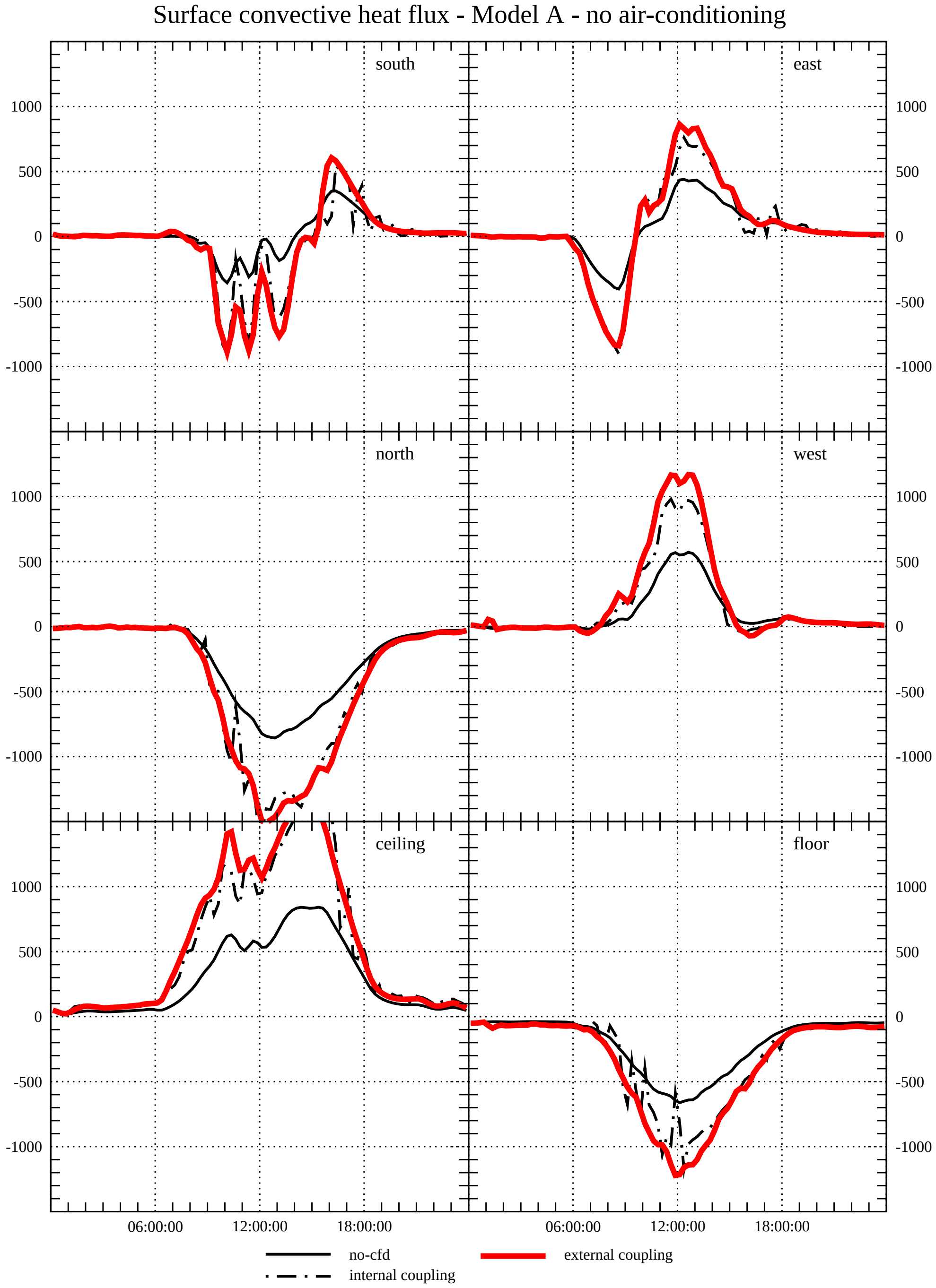


Figure 5.27 Convective heat flux (Model A)

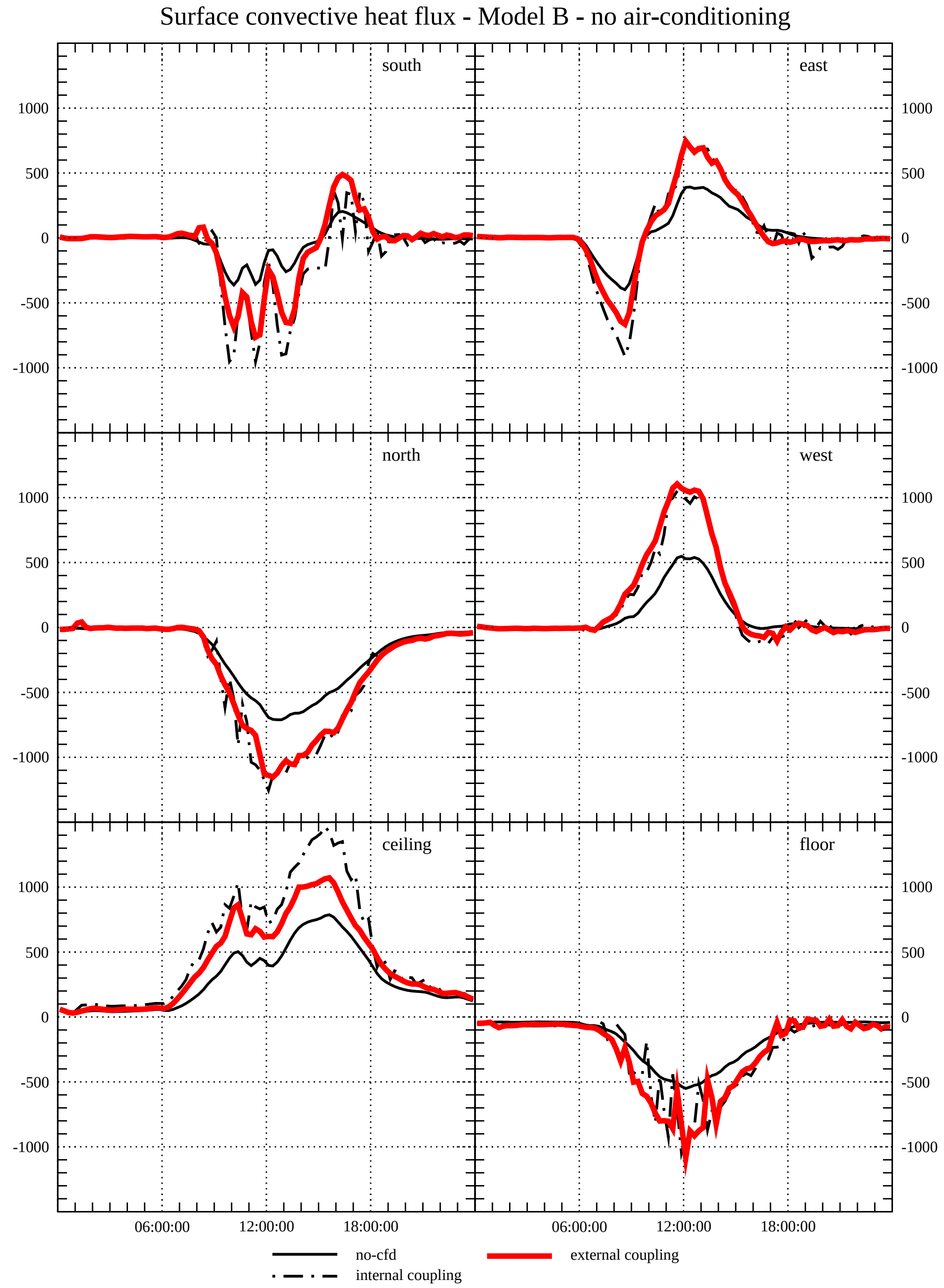


Figure 5.28 Convective heat flux (Model B)

5.3.5.6 Air velocity distribution

Figure 5.29 shows the air velocity vectors in a Y-Z section, corresponding to the same section as the measurement section in Figure 5.30. In the first 3 graphs (06:00, 08:00 and 10:00) the prediction of air velocity vectors cannot be compared with confident with the measurement result. The measurement shows a very small magnitude of velocity with a flow that seems to be highly 3-dimensional that is very difficult to capture in 2-D section. At 12:00, the predictions are closer to the measurement result, even though the re-circulation patterns in the top corners are not evident in the experiment result, most probably because of the small number of measurement locations. In the last 3 graphs (14:00, 16:00 and 18:00), the simulation can predict the air flow pattern more closely to the experiment result.

5.4 Case 3: IEA Annex 26 Atrium – mixed convection

5.4.1 Case descriptions

The case is the same as Case 2, except that the air conditioning is now activated during the experiment. The air conditioning has a maximum capacity of 32 kW and capable of supplying air at 4050 m^3/hr.

During the measurement, the air velocity is fixed at 1.4 m/s at the inlet, and the inlet temperature varies between 13 – 40 °C when the outside temperature is above 13 °C. The air conditioning is activated between 06:00 and 18:00. The set point temperature for summer is 25 °C.

The experimental data used for this case was from 05-Apr-1995. The measurement setting, methodology and results are well-documented and can be found in Murakami et al. 1994.

5.4.1.1 BES model

The geometry and material properties are exactly the same as the previous case. The only difference is that in this case there is an HVAC system. However, there is no explicit HVAC plant definition to be used. The HVAC system is simply modelled as heat flux injected to the zone. The additional simulation settings to be set are (1) the actual cooling capacity used for the measurement and (2) how to treat outdoor air. These two issues are discussed in the model calibration section below.

5.4.1.2 CFD model

The CFD geometry is more or less the same with the previous case. The only difference is the definition of a supply and exhaust opening in the north wall. The area of the openings however is not the actual dimension of the opening, but rather the equivalent opening area was used. Hiramatsu et al. 1996 estimated the value to be 0.041 m^2 and 0.035 m^2 for both the supply and exhaust openings, both are modelled as slot opening of 0.2mx0.2m.

The flow rate is also estimated by this opening area which is 1.4 m/s x 0.041 m^2 = 0.0574 m^3/s. The exhaust velocity is estimated by this flow rate and the equivalent opening area: 0.0574/0.035 = 1.64 m/s. However, as a simplification, in the CFD simulation both openings have the same area so the boundary condition is defined as the same constant velocity of 1.4 m/s (with opposite directions).

5.4.1.3 Model calibration

The next problem is to estimate the actual cooling capacity as used in the measurement. Setting the cooling capacity to the maximum cooling power (of 32 kW) resulted in huge discrepancy between the simulation and the measurement. The measured air temperature was never reached the set point temperature, while in the simulation (using the maximum cooling power) the air temperature easily reached the set point. This indicated that partial cooling capacity was used during the experiment.

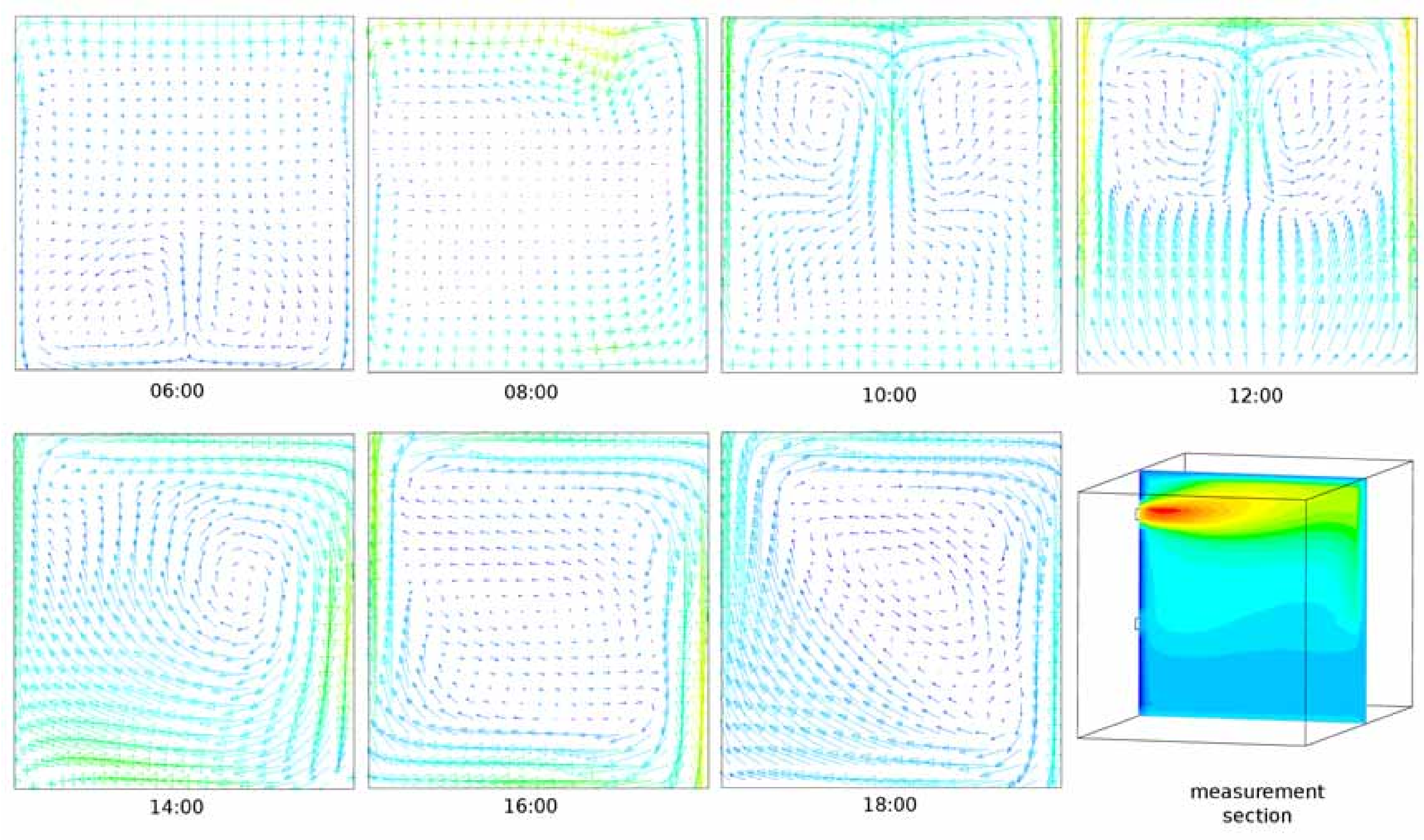


Figure 5.29 Air velocity prediction in Y–Z section for natural convection case

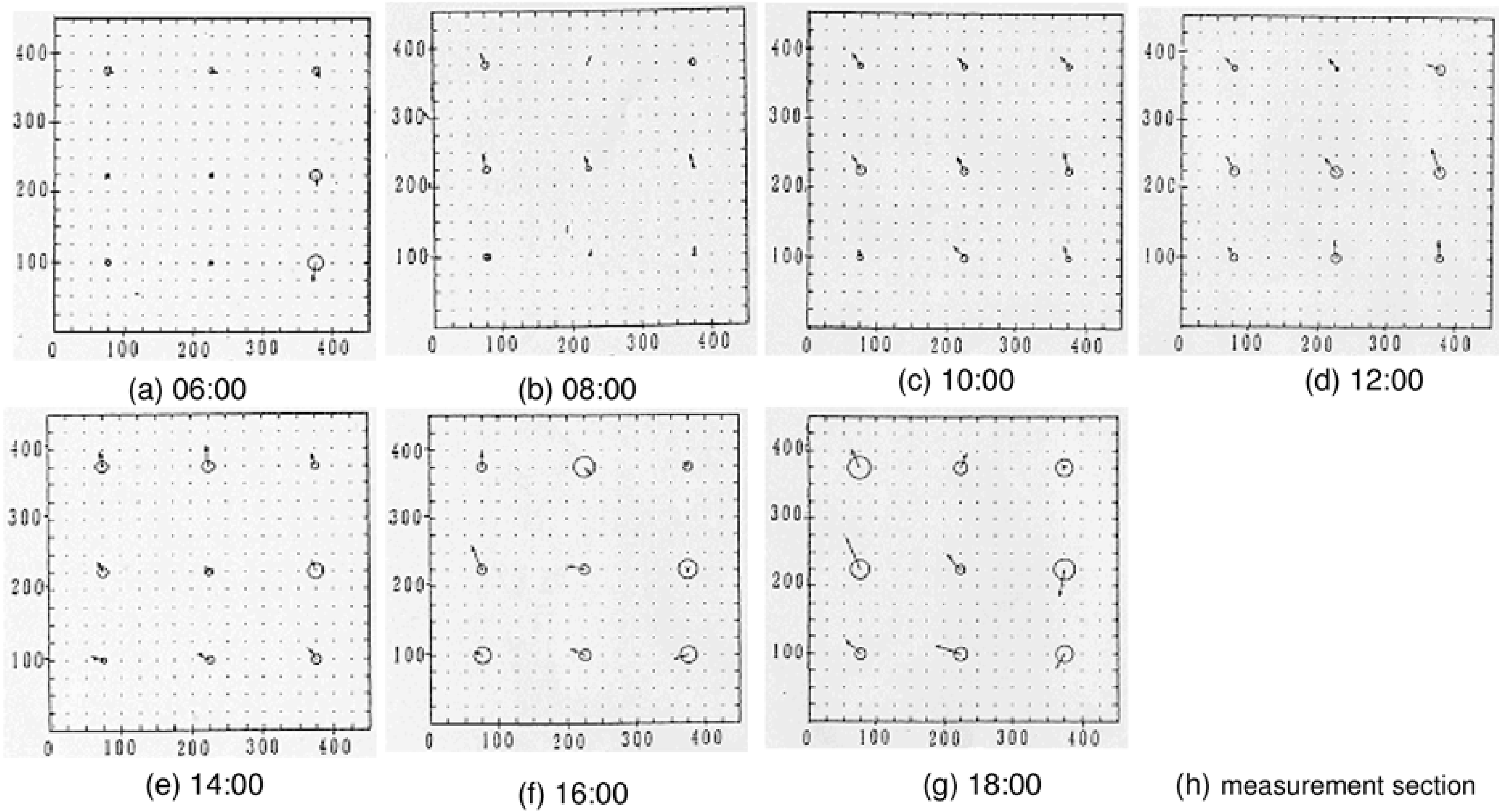


Figure 5.30 Measured air velocity distribution in Y–Z section at X=3.95m (Arrow shows air velocity vector, radius of the circle represent the turbulence intensity). Graphs from Murakami et al. 1994

From the measurement data, the maximum temperature difference between supply and exhaust is around 20 °C. Using the flow rate estimated above, the heat extraction rate is estimated to be 1.5 kW. This value is used to define the cooling capacity of the HVAC system.

5.4.2 Validation results

5.4.2.1 Computation time

As in earlier cases, the CFD coupled simulations, both internal coupling and external coupling, used the zero equation model. Both also used the same convergence criteria (i.e. 10^{-6} residuals error for energy and 10^{-3} for others). The iteration for CFD simulations were limited to 1000 iterations, and the iteration always starts from the latest data from the previous time step.

The same trend on the computing time of internal coupling is observed as in the previous case. On the simple model, with a mesh of 10x10x10, internal coupling case took only 43 minutes. When the mesh was refined, due to the geometrical demand to include the frame, to 19x14x14 (less then double), the computing time became more than 4 hrs (almost four times). The external coupling, on the other hand, can use a finer mesh (uniform grid size of 0.2m) with a more or less similar computing time.

Table 5.5 shows the summary of the simulations carried out for this case.

Table 5.5 Simulation settings and time for Atrium Case with Air Conditioning

Model	CFD	Mesh	Time
Model A	No CFD	n.a.	0:01:44
Model A	Internal coupling	10x10x10	1:38:52
Model A	External coupling	35x23x23	7:59:57
Model B	No CFD	n.a.	0:03:53
Model B	Internal coupling	19x14x14	7:01:40
Model B	External coupling	35x23x23	8:59:14

5.4.2.2 Room air temperature

Figure 5.31 and Figure 5.32 show the comparison between the measurement and simulation results of the air temperature. As before, the measured air temperature is actually an average value from 27 measurement points. It is important to note the error involving the use of average value for comparison. The air temperature inside the room cannot be considered uniform as in the previous case. The air temperature is highly non-uniform especially during the peak temperature (at 13:00hrs) where the minimum and maximum temperature difference reaches 7.5 °C.

As shown in those figures, the temperature prediction has the similar trend as in the previous case. Different from the earlier case, the introduction of higher CHTC (by employing the coupled simulation) results in higher temperature prediction, and that makes the prediction to be closer to the measurement data as presented in Figure 5.31 and Figure 5.32.

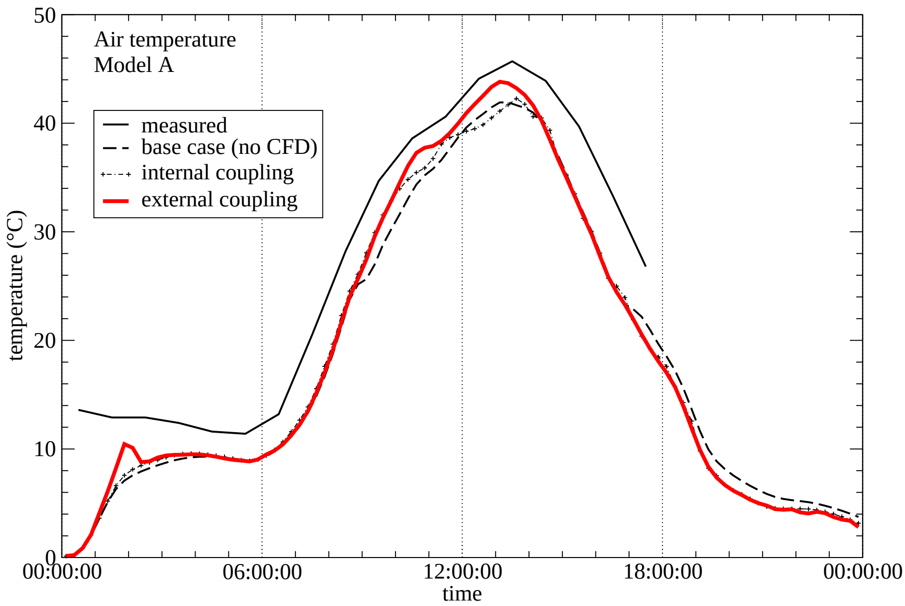


Figure 5.31 Air temperature (Model A)

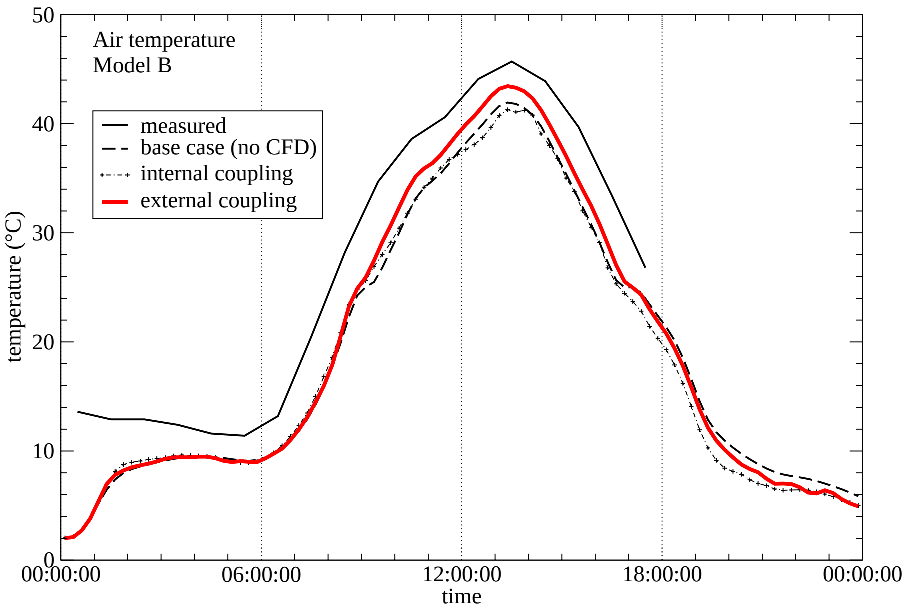


Figure 5.32 Air temperature (Model B)

5.4.2.3 Wall temperature

Figure 5.33 and Figure 5.34 show the internal surface temperature for Models A and B. The predictions show reasonable agreement with the measurement data. In general there is a tendency to underestimate the prediction of surface temperature, except for south and east surface. There are differences in the peak temperature of around 4 – 6 °C. This error can be attributed solely to the data input error, especially the data for optical properties as explained in Section 5.3.4.

The ceiling surface temperature is not sensitive towards the CHTC where the uncoupled predictions were relatively the same as the coupled simulation predictions. For other surfaces, the surface temperature shows a slight sensitivity towards CHTC value. The differences are mainly observed in the peak temperature predictions, where the difference between uncoupled and coupled simulation prediction could reach 2 °C.

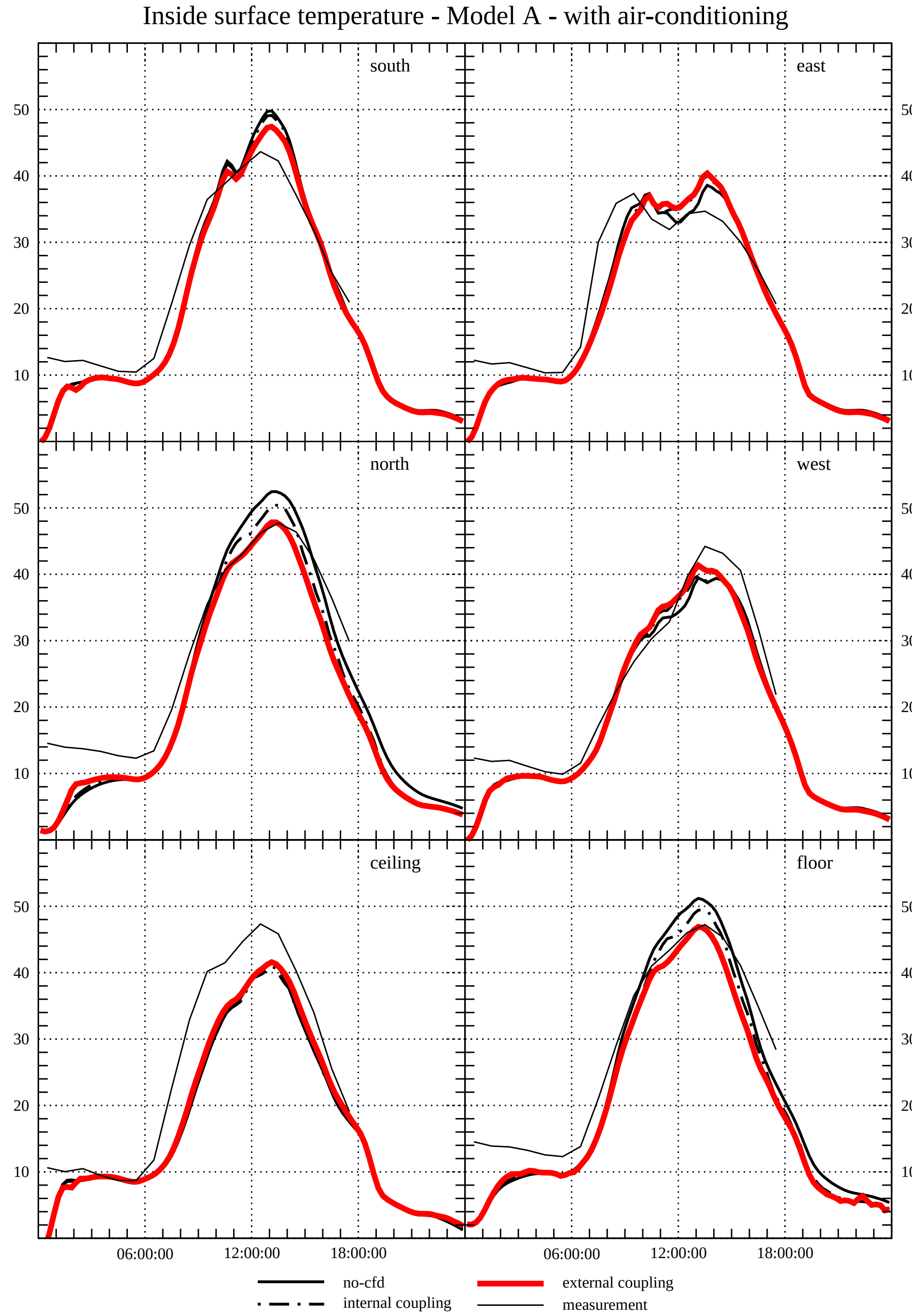


Figure 5.33 Wall temperature (Model A)

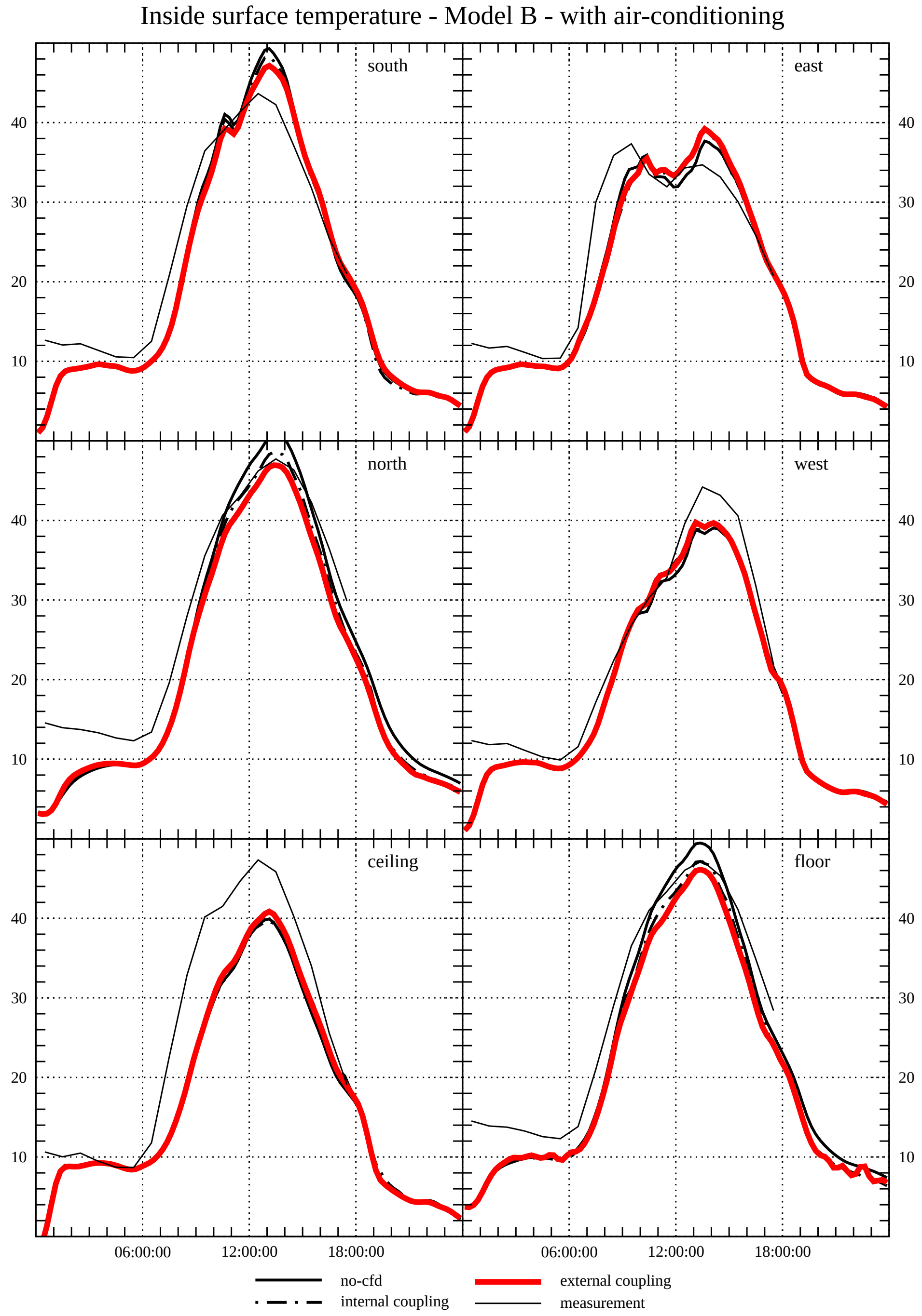


Figure 5.34 Wall temperature (Model B)

For Model B (Figure 5.34), the surface temperature is the average of the glass part of the wall. As can be seen, there is no significant difference between the surface temperatures predicted with Model A and with Model B.

5.4.2.4 Comparison of temperature prediction with previous research

Figure 5.35 shows the comparison of temperature predictions between the measurement data, external coupling result, and the result from previous research (Zhai 2003). External coupling method shows better agreement with the measurement data, although both simulations underestimated the prediction. For south wall, the internal coupling shows better agreement with the measurement data, while the external coupling over-estimated the peak temperature by 5 °C.

Both simulations have similar prediction of surface temperature for the north wall and the floor. The main difference is that for the external coupling the temperature decays in faster rate in the afternoon hours. This error can be associated with the error in material properties definition.

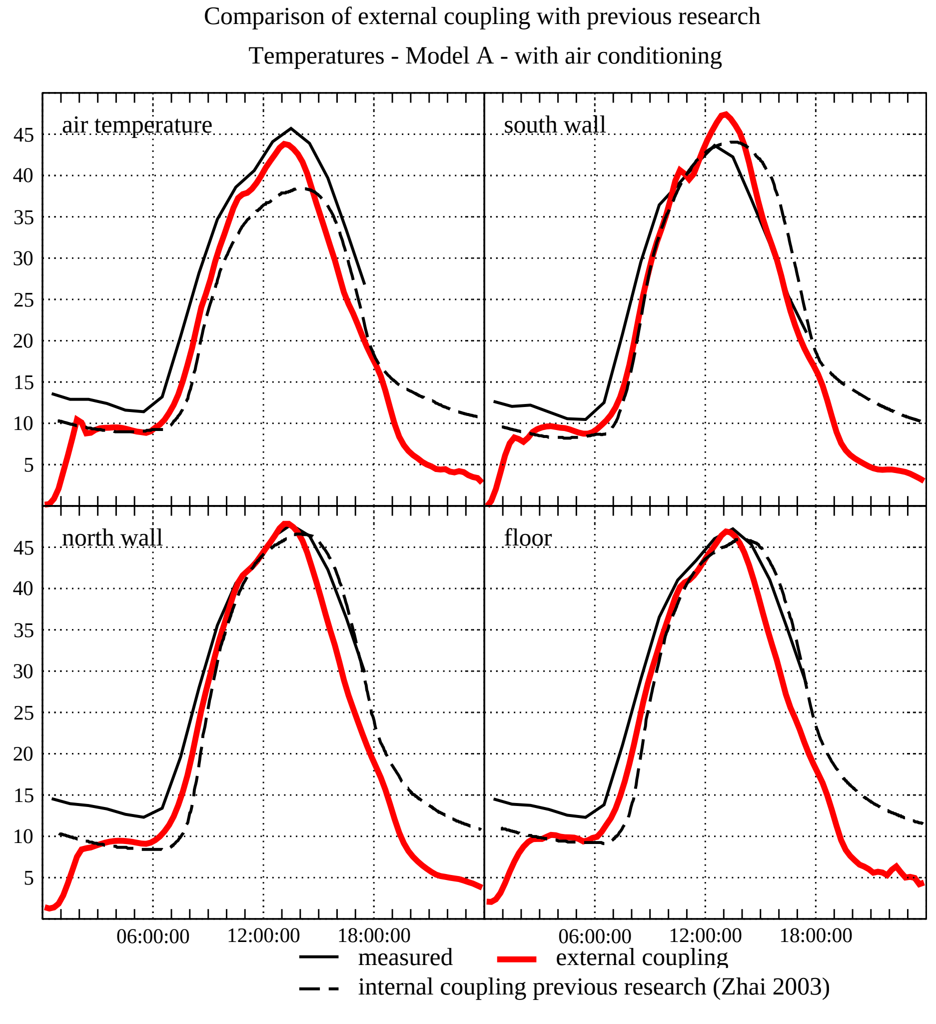


Figure 5.35 Comparison of temperature prediction with previous research

5.4.2.5 CHTC

Figure 5.36 and Figure 5.37 show the CHTC for Model A and Model B. As in the previous case, the fluctuation in the coupled simulation result (both internal and external coupling) shows the coupling controller in action where it can reject the calculated value sent from BES to CFD.

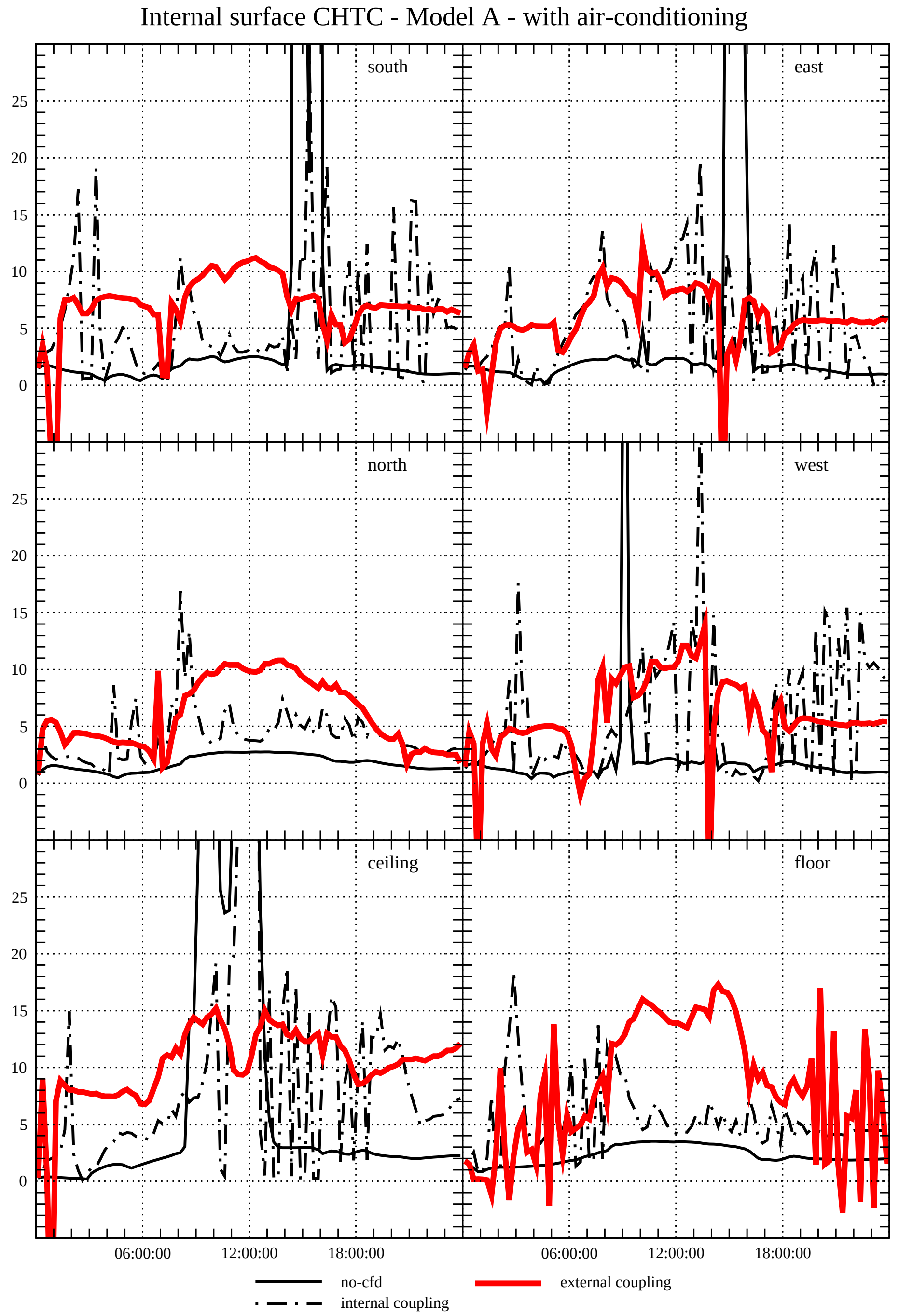


Figure 5.36 CHTC (Model A)

The same trend as in the previous case is observed. CHTC calculated by external coupling were rejected less frequently, while internal coupling case was rejected more frequently.

For this case the CHTC for uncoupled (no-CFD) simulation, which was the base case in the comparison, was calculated using Fisher method (Fisher 1995), as was already implemented in ESP-r for mixed convection regime. This case actually has a very low air flow rate (1.5 ACH) that is lower than the range of applicability of Fisher correlation, which is 3 – 100 ACH. However, there is no attempt to use another correlation as this is only the base case value, and for coupled simulation this value will be overridden by the CHTC value calculated by the CFD.

Another problem that comes from the CHTC correlation is the very high CHTC value observed in Figure 5.36 (on the south wall at 15:00 for the base case and the internal coupling, and also on the west wall and the ceiling at different times) and in Figure 5.37 (on the west wall at 14:30 for the external coupling simulation). The values are far beyond the scale of the graphs, and they were in the order of hundreds.

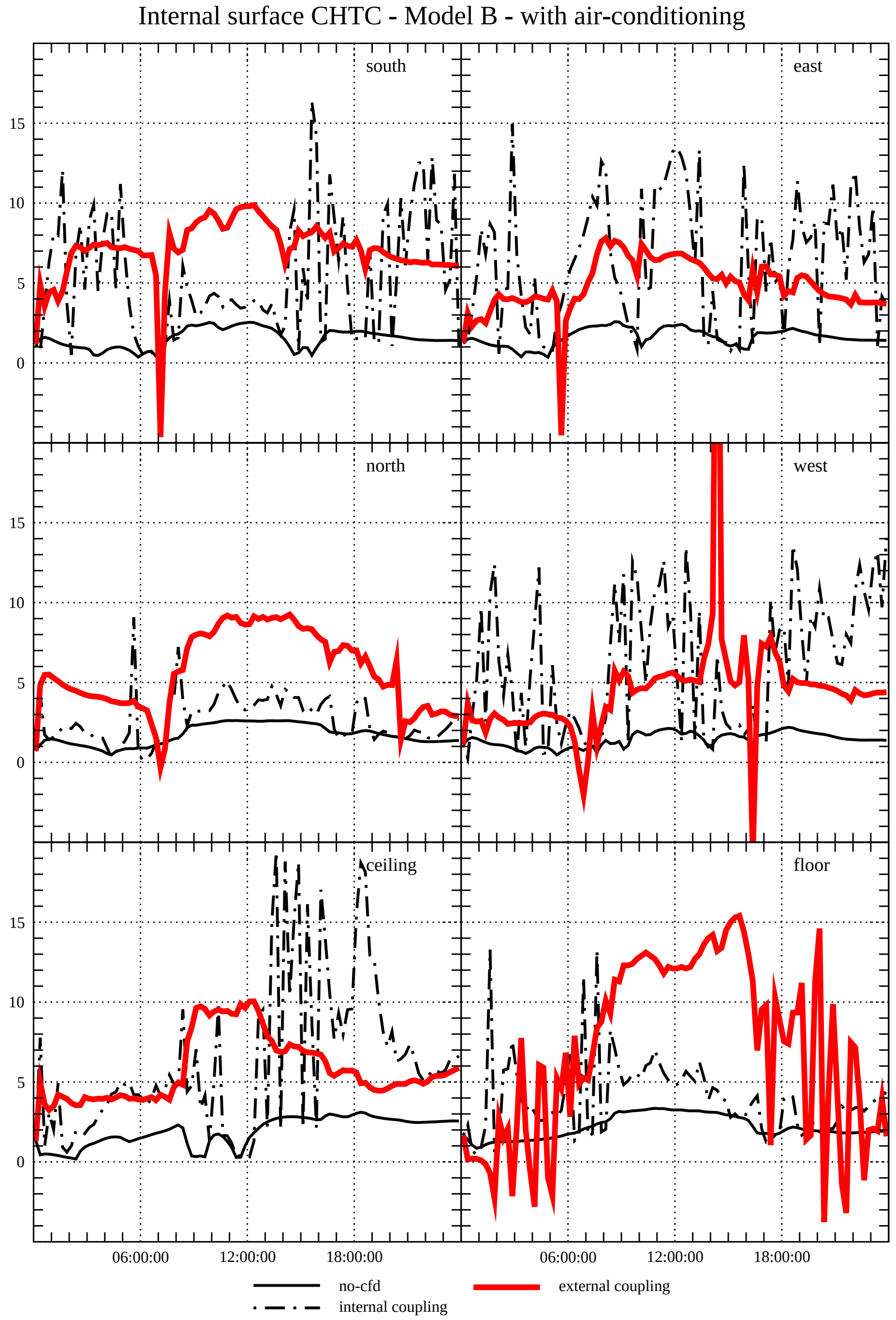


Figure 5.37 CHTC (Model B)

The problem is not on the selection of the correlation, but on how the correlation is implemented in the program. Fisher correlation uses supply air temperature as the reference temperature for CHTC calculation, while ESP-r uses the room air temperature as the reference. ESP-r scales the Fisher correlation to resolve this difference in reference temperature using the following equation (Beausoleil-Morrison 2000):

$$h_{c,ESP-r} = h_{c,FISHER} \frac{T_{surf} - T_{diffuser}}{T_{surf} - T_{room-air}} \tag{5.8}$$

where:

$h_{ic,ESP-r}$	:	CHTC used by ESP-r
$h_{ic,FISHER}$	:	CHTC calculated by Fisher correlation
T_{surf}	:	surface temperature
$T_{diffuser}$	:	air temperature at the diffuser
$T_{room-air}$	:	room air temperature

The problem comes when the surface temperature is equal with the room air temperature, then the CHTC will be infinitely large. In the source code (ESRU 2003) this problem is avoided by setting the scaling factor to 1000. But still, this will result in a very large CHTC value.

On these unfortunate events where the air temperature equals the surface temperature, the coupled simulation actually calculated the correct CHTC value. For example in Figure 5.37 in the west wall at 15:15, the Fisher correlation gives a CHTC value of 0.132 W/m^{2}K. But the scaling factor was so big because the surface temperature was very close to the air temperature, which then gives the CHTC value of 129 W/m^{2}K. The external CFD actually gave a reasonable value of CHTC. However, the value becomes too large after it was scaled by the above equation, and hence it was rejected.

The rejection was not because the CHTC$_{CFD}$ value was too large compared to CHTC$_{empirical}$, but it was because it was too small.

For the internal coupling, the blame is not only to the CHTC correlation. For example in Figure 5.36 in the ceiling at 12.45, the CHTC calculated by the Fisher was 0.066 W/m^{2}K. Again the scaling factor was so big that the scaled value was 94 W/m^{2}K, which was too big. But the CFD came with even bigger value of 265 W/m^{2}K. This bigger CHTC$_{CFD}$ value was accepted, because according to the same filter as above, due to the large value of CHTC$_{empirical}$, the CHTC$_{CFD}$ fell within acceptable range. Hence, the 265 W/m^{2}K was accepted as the CHTC value as presented in Figure 5.36.

This above discussion shows that on certain condition, the post-CFD process fails not only to filter out the false value, but it also fails to accept the more accurate value. A correction has been made to the decision making mechanism so that on these conditions, the post-CFD process can filter out the less accurate value and accept the more accurate value.

5.4.2.6 The effect of frame

The reason for including Model B is actually to study the effect of including the details of the frame construction into the model. Schild (1997) found that the heat transfer through the frames are very significant so that it should not be left out. However, so far in the discussion of the simulation results, there is no obvious difference between Model A and Model B.

Figure 5.38 shows the comparison of air temperature prediction between Models and B. The predictions are similar to each other. The main difference is that the prediction of Model B was lagged behind due to the thermal mass of the frame. The surface temperature predictions also show the same trend.

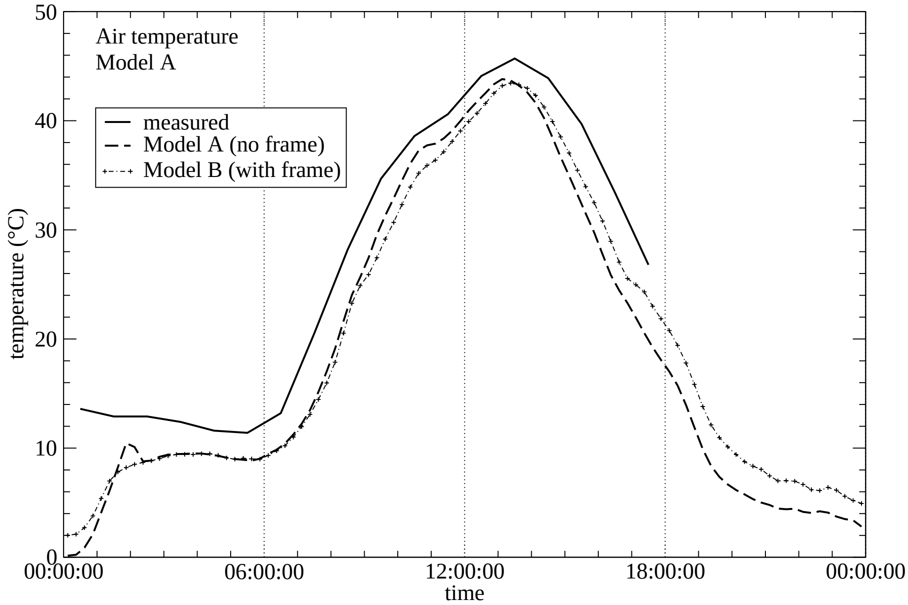


Figure 5.38 Air temperature comparison between Model A and Model B

Figure 5.39 shows the energy demand comparison for Model A and Model B. There is no significant increase in energy demand due to the frame. The uncoupled simulation shows less than 2% increase. The external coupling shows 3.4% increase in the energy demand. Curiously, the internal coupling predicts a slight decrease in energy demand.

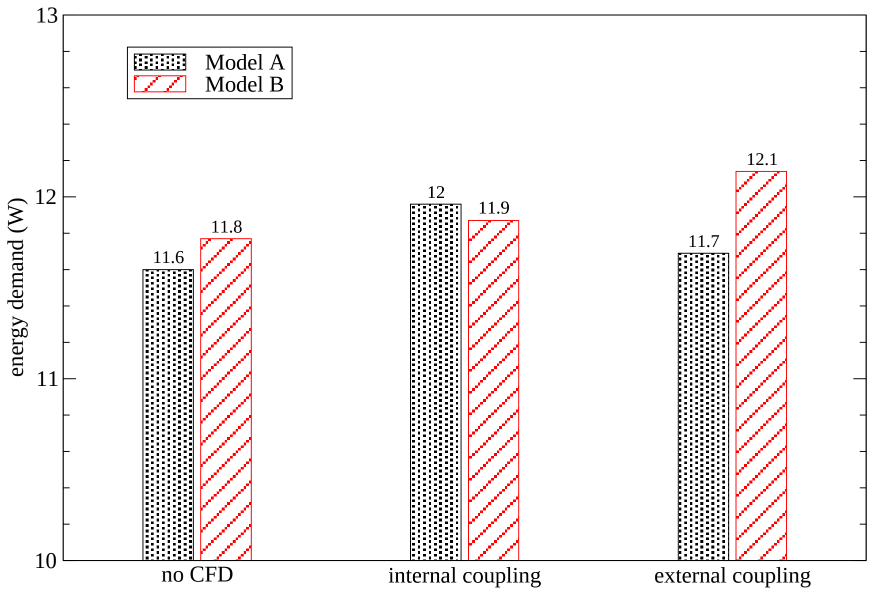


Figure 5.39 Energy demand comparison

5.4.2.7 Velocity Vectors

Figure 5.40 and Figure 5.41 show how air velocity changes in the atrium throughout the day, both in simulation and experiment. Both are from the same section in the atrium.

In the morning, the cold air going in will be drawn up and attached to the ceiling until it warms up and hit the opposite wall. As the sun rises and the ceiling and walls heat up, the flow pattern changes, most noticeable in the direction of air flow on the wall opposite to the inlet.

The coupled simulation succeeds in capturing the dynamic of the airflow pattern that would be difficult (if not impossible) with other simulation method.

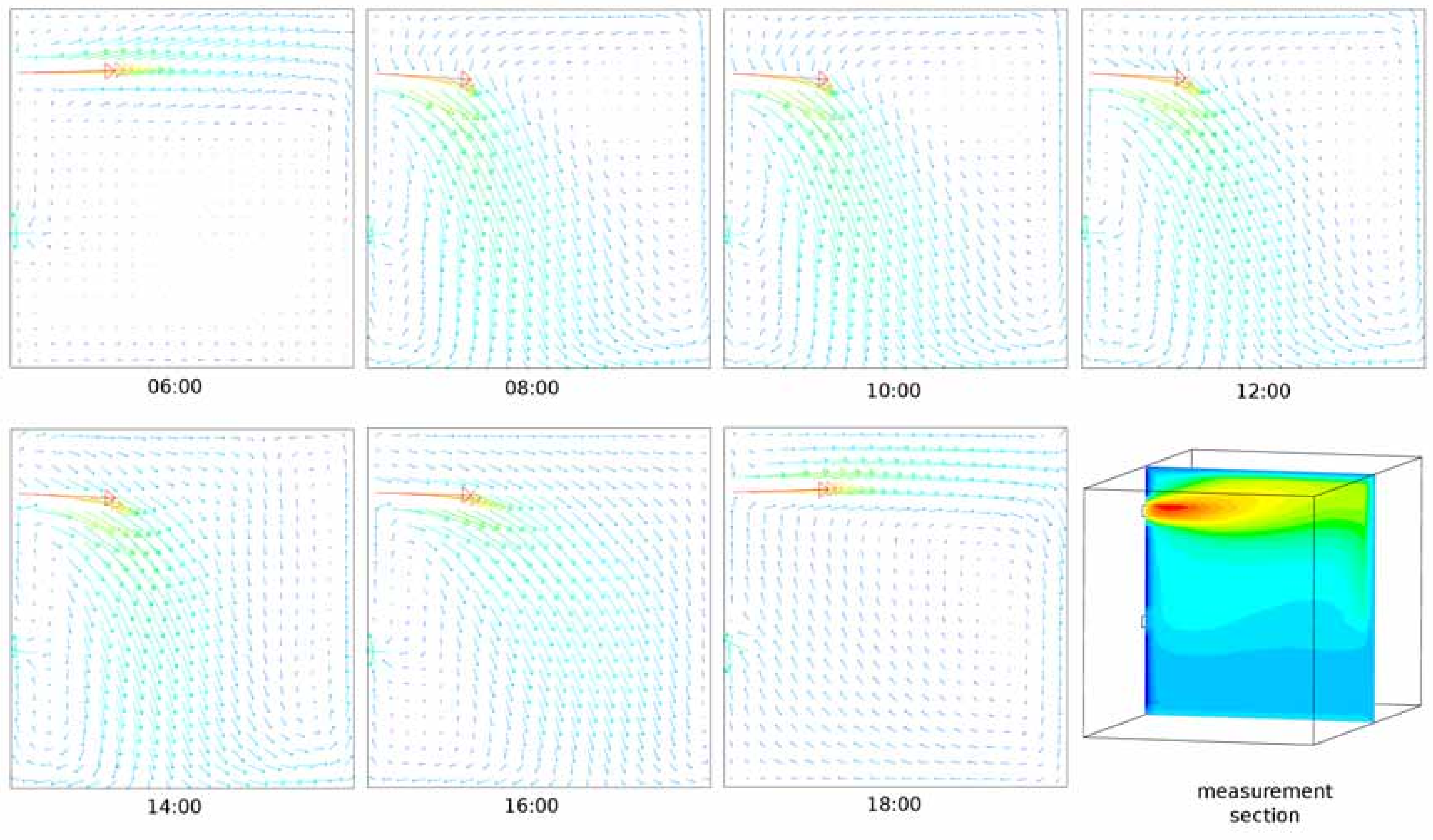


Figure 5.40 Air velocity prediction in Y–Z section for mixed convection case

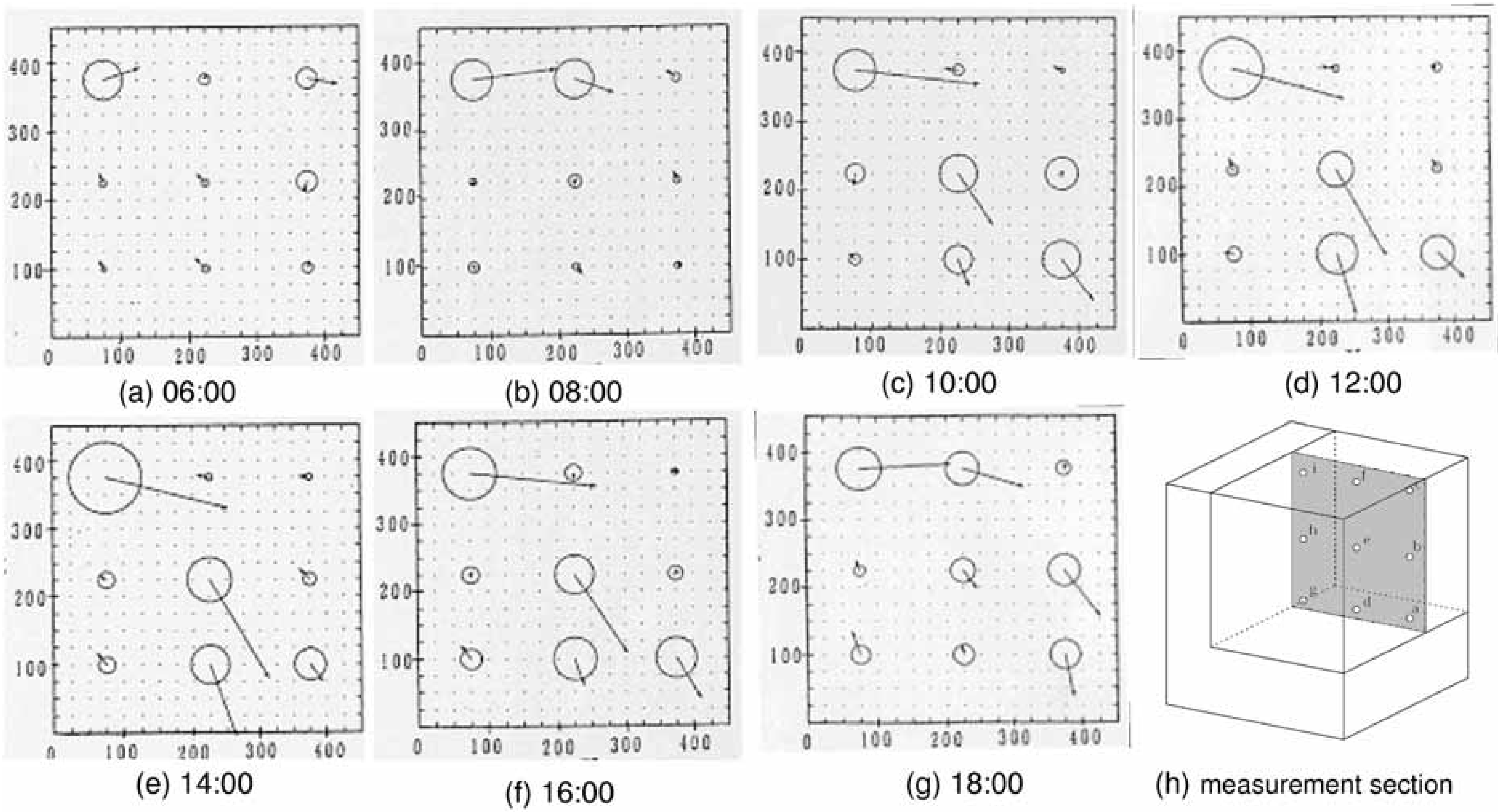


Figure 5.41 Measured air velocity distribution in Y–Z section at X=3.95m (Arrow shows air velocity vector, radius of the circle represent the turbulence intensity). Graphs from Murakami et al. 1994.

5.4.2.8 Temperature distribution

Figure 5.42 shows the measurement points for air temperature. The CFD predicted temperature distribution is compared to the experimental result in Figure 5.43. The temperatures and heights are normalized using the following equation:

$$T = \frac{T_{air} - T_{inlet}}{T_{exhaust} - T_{inlet}} \tag{5.9}$$

where: T_{air} : air temperature at measurement points

T_{inlet} : supply air temperature

$T_{exhaust}$: exhaust air temperature

$$H = \frac{h}{H_{ceiling}} \tag{5.10}$$

where: h : height of the measurement points

$H_{ceiling}$: height of the ceiling (=4.5m)

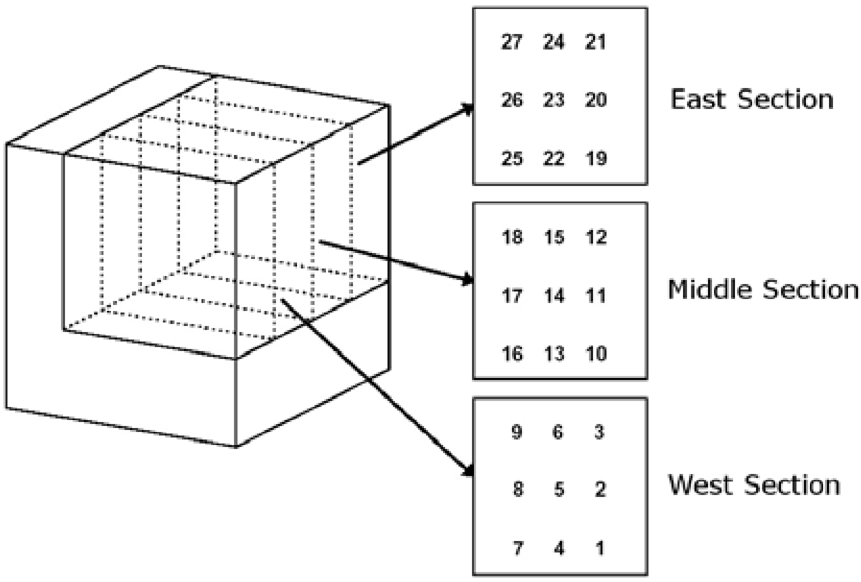


Figure 5.42 Measurement points for air temperature

Figure 5.43 also shows the internal coupling results from earlier research (Zhai 2003). The results of external coupling are similar to the results of internal coupling. However, the agreement with the measurement data is not very well.

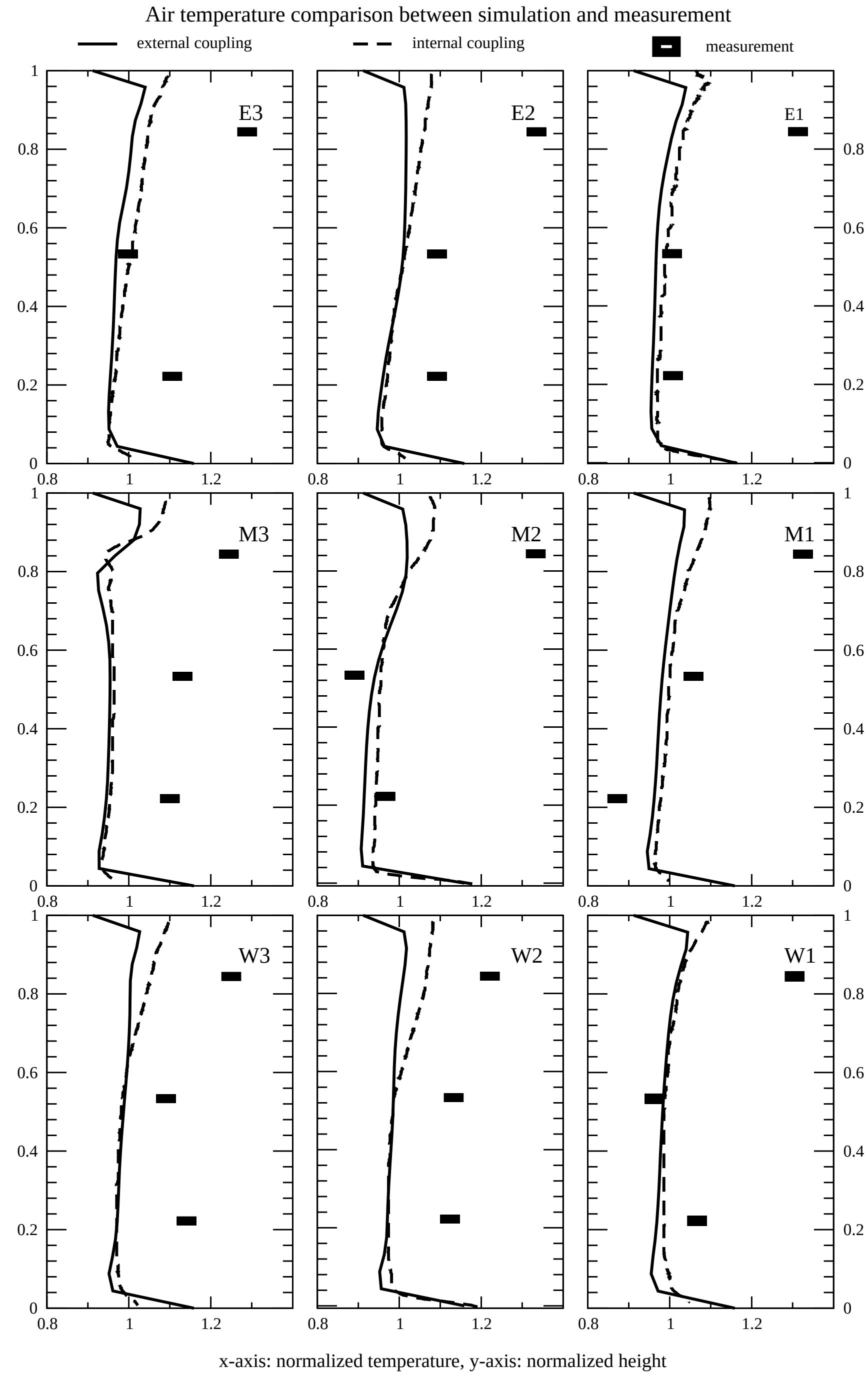


Figure 5.43 Air temperature comparison between simulation and measurement (top: east section, middle: middle section, bottom: west section). Internal coupling results were taken from Zhai 2003.

5.5 Conclusions

This chapter presents three cases as validation study which covers different HVAC system (heating with radiator, cooling with all-air system) and different type of airflow (natural convection, mixed convection). ESP-r has an advanced mechanism in the coupling of CFD and BES. However, as shown all cases, the advanced coupling mechanism is hindered by the limitations of the CFD solver.

The traditional internal coupling approach to overcome this situation is to revisit the source code and develop a better solver. As an alternative to that approach, the external coupling method uses an external CFD program to overcome the limitation.

This chapter also shows how the validation exercise can be used to give feed back in the software development process. In the validation process, the result should always be used to improve the software.

This validation study clearly shows that external coupling method (between CFD and BES) offers some advantages over the other simulation method. It has everything that internal coupling has to offer, for example the capability to simulate the dynamical changes in room airflow patter over the simulation period, with at least the same accuracy.

Some of the simulation results are not satisfactory, especially the quantitative CFD results. CFD seems to be able to produce good CHTC values for energy calculation, but unable predict accurate temperature distribution far from the surfaces. Both internal coupling and external coupling suffers the same inaccuracy. At this point it is important to think about the possible scenarios to improve the coupled simulation.

For sure there will be developments on the CFD simulation side. For internal coupling, the only way to absorb the future developments is to write the code into the program, which of course will take many man hours of work. For external coupling, on the other hand, all of future developments will be available in an instant they are made available in any CFD package.

The external coupling offers the flexibility for selecting the best CFD package available (with all its new developments) as a matter of plug-and-play.

To put everything into perspective, it is important to note that this chapter shows the advantage of external coupling in terms of speed and software maintenance. Other aspects of integrated simulation may (or may not) favour the internal coupling. One example is the control system action. This particular aspect is an on-going research that will be reported in the near future (Yahiaoui et al. 2004).

Chapter 6

Applications

This chapter describes the application of coupled simulation to show the usefulness of the work proposed in this thesis. The selected case is the thermo-active concrete core system. The guideline presented in Chapter 3 is used to assess the necessity of coupled simulation. The results show that the coupled simulation does have significant role to achieve a better, more accurate, design decision.

6.1 Introduction

This chapter presents the application study for the work presented in this thesis. The purpose of the application study is to highlight the benefits of the coupled simulation. After the introduction and the description of the building, the guideline presented in Chapter 3 will be used to assess the necessity of the coupled simulation for current problem. The results of the coupled simulation will be presented at the end of this chapter.

This study uses a relatively simple (a rectangular geometry) and small (small number of cells for CFD mesh) model. This is intentional as the purpose of this study is to highlight the benefits of the coupled simulation. A more complex model will have many other parameters to consider that could obscure the main purpose of this study.

6.2 Simulation of thermo-active concrete core

6.2.1 Background

The thermo-active concrete core system (TACS) has long been recognized as an alternative to the conventional all-air system, especially in Europe. In all-air system, the heating, cooling and ventilation are all handled by air, where the heating and cooling requirements determine the amount of air needed by the system. Both thermal comfort and indoor air quality criteria are achieved by air flow.

TACS is part of radiant heating and cooling systems where the main heat exchange mechanism for heating and cooling is done by radiation. The idea is to change the medium for main heat transfer mechanism from air to water which has more efficiency. Moreover, the heating and cooling criteria can be met by different mechanism than the ventilation criteria.

The use of radiant panels is one example of radiant heating and cooling system. TACS takes it a bit further to include the thermal mass of the concrete as part of the system by delivering water through pipes embedded in the concrete. In this way, the concrete is acting as heat storage for the system.

Even though the main heat transfer mechanism for this system is radiation, on some cases, the convective heat transfer also plays an important role. On cooling condition, the TACS is usually combined with the displacement ventilation to deliver the air to meet the air quality requirements. It is interesting to study how the use of coupled BES-CFD simulation can help to achieve a better design decision.

This section discusses the possibility of using the coupled CFD and BES to simulate the TACS, in particular to highlight the potential of the external coupling mechanism. After the description of the case study, BES-only simulation results will be reported and used as the reference case. Based on the results of the BES-only simulation, the potentials of the coupled simulation will be identified. In the final section, the results of the coupled simulation will be presented.

6.2.2 Description

The case involves an office space where the floor to ceiling height is very high (Figure 6.1), similar to the case described earlier in Chapter 3. The use of an all-air system is not attractive because of the high volume of unoccupied space in combination with high glazed area. TACS in combination with displacement ventilation is one alternative to be explored. With a high glazed area covering the whole west side, the challenge of the design is to provide a comfortable work area for workstation A and B (see Figure 6.1) whose working spaces are next to the glass wall.

In summer condition the west glass wall will have a shading device rolled from the top of the wall down to 2m above the floor. For simplification, the internal shading device is modeled as external shading in the BES model as shown in Figure 6.1.

Figure 6.2 shows the temperature predictions from BES-only simulation for free-floating condition with a small infiltration rate. The zone air temperature represents the dry bulb temperature of the whole space (as a well-mixed assumption is used by BES). The MRT and operative temperature, however, are for the area near the glass wall (in workstation A, see Figure 6.1). The floor temperatures show a great variation of around 7 °C, while the glass wall shows even more drastic variation (more than 15 °C). The ceiling, due to its thermal mass, shows only around 3 °C variations.

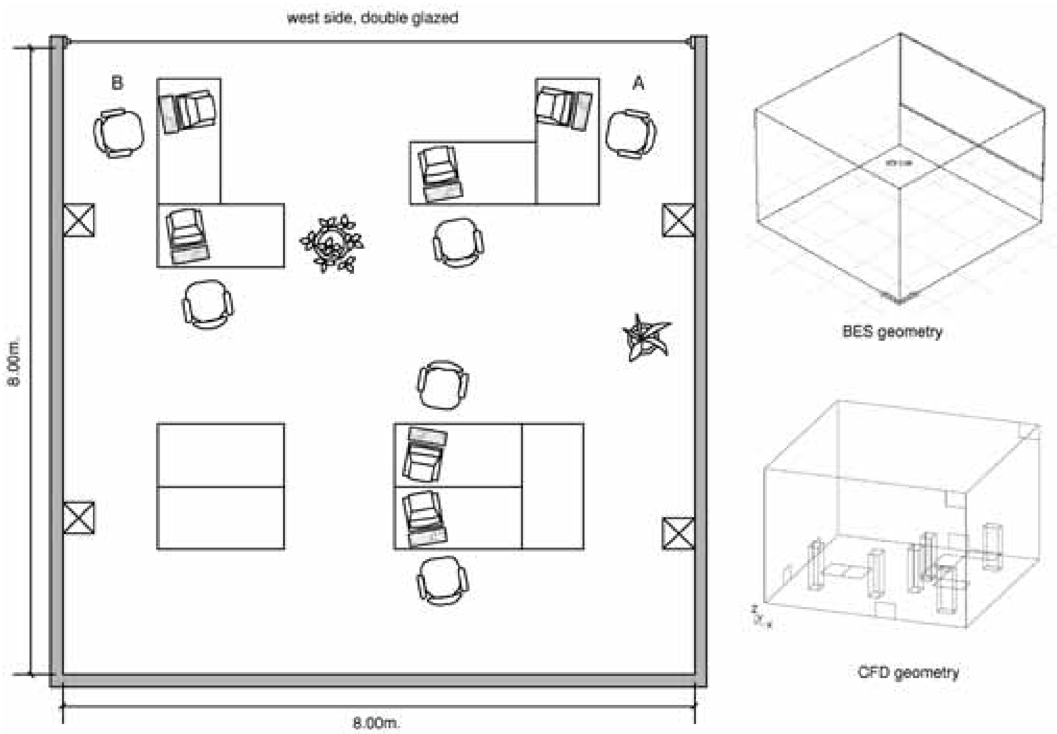


Figure 6.1 Layout of the space

Based on the result of free-floating condition, the use of TACS is interesting. The ceiling temperature only fluctuates around 3 °C under severe summer condition, so that it needs to be studied further whether keeping the ceiling temperature down will make the operative temperature in an acceptable level.

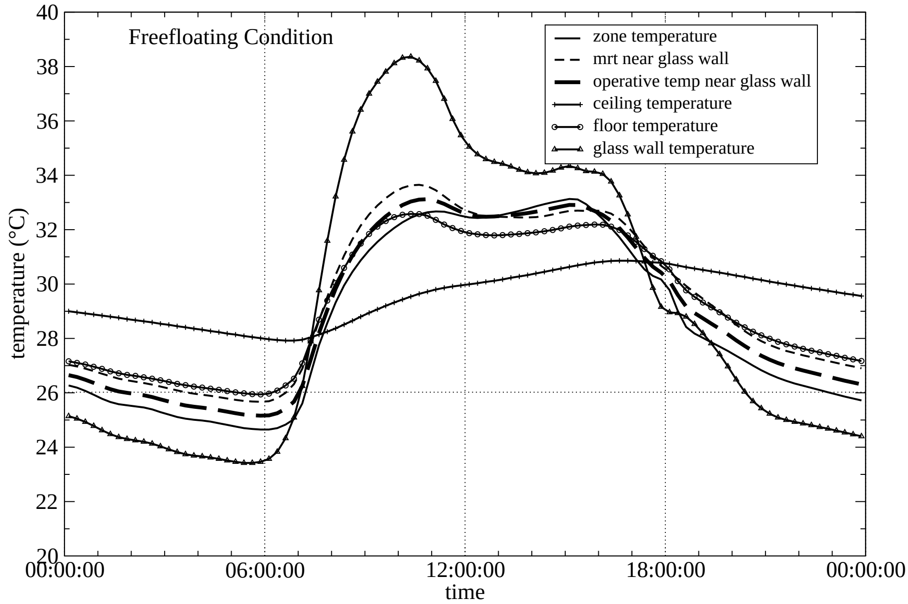


Figure 6.2 Temperature prediction for free-floating condition

Several scenarios are considered for this study. Scenario 1 considers the all-air scenario as the base case. Because of the large space and the potential radiation problem from the high glazed wall, the operative temperature is used as the controlled variable (Figure 6.3).

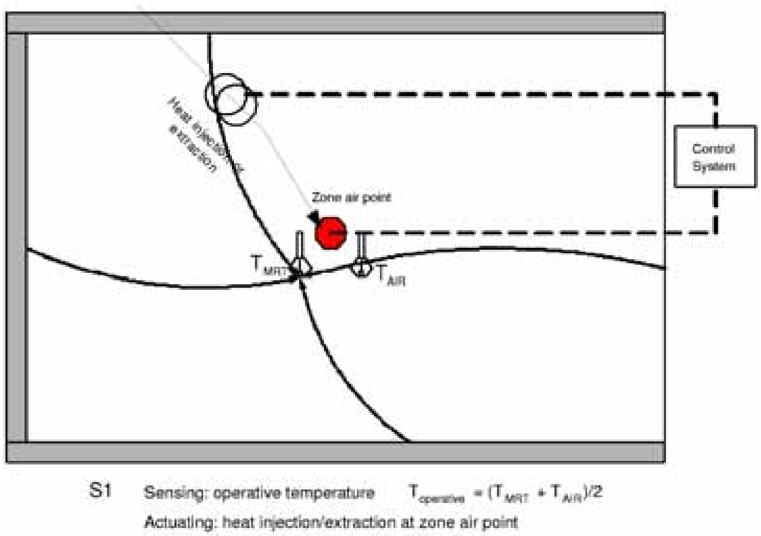


Figure 6.3 Control system for Scenario 1

Control system for TACS is actually more complicated than the conventional all-air system. The heat injection or extraction is occurred in the core of the concrete which has large thermal mass. This will cause a large response time from the time an action is sent to inject or extract the heat until the result can be sensed in the occupied zone. Furthermore, as radiation is the main heat transfer medium for this system, the operative temperature is used as the controlled variable.

Two scenarios are used for TACS simulation in this study. In Scenario 2 the zone dry-bulb temperature is used as the controlled variable (Figure 6.4). Note that the controlled variable is not the operative temperature because of the software limitation. Several test simulations were carried out to calibrate the control system. The tests show that a set point of 23 °C can be used to achieve comfortable condition in the space.

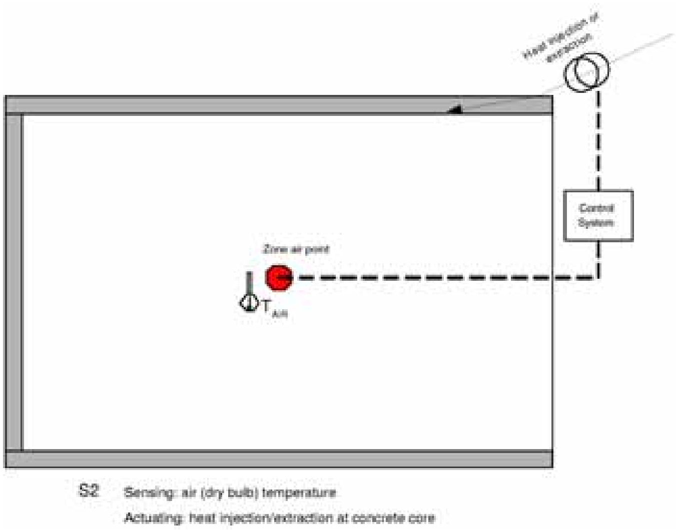


Figure 6.4 Control system for Scenario 2

Scenario 3 tries to mimic a more complex control strategy (Figure 6.5). Scheatzle (2003) used a nested control system for simulating a TACS system in a house. Operative temperature was used as the main controlled variable. Every time the operative temperature changes significantly, the surface temperature of the concrete is increased or decreased in steps of 1 °C.

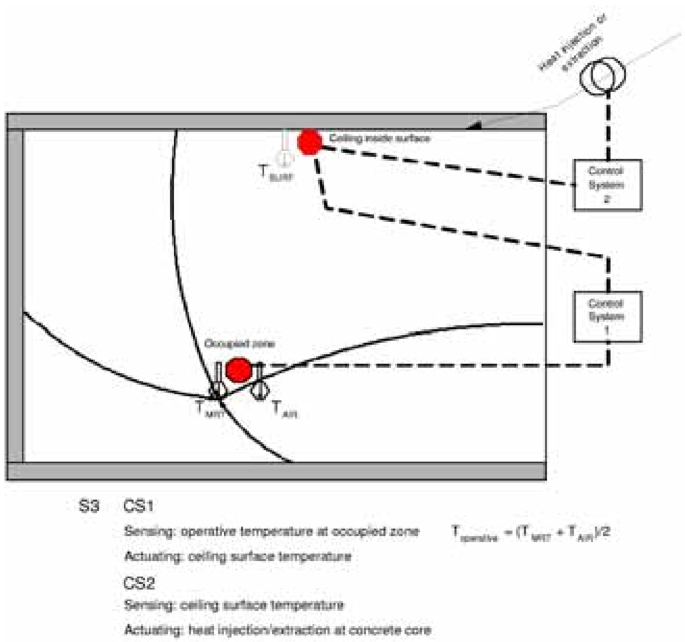


Figure 6.5 Control system for Scenario 3

However, such a complex control strategy with nested control loop cannot be used due to software limitation. For simplification, Scenario 3 uses the ceiling internal surface temperature as the controlled variable.

Operational strategy was also tested in Scenario 3. The surface temperature were kept at a certain temperature before occupancy hours, and then released to free-float until reaching a certain temperature. After occupancy hours, the system was again released to free-float. With this operational strategy, the actual cooling can be done outside office hours with potential savings from off-peak hours electrical charge.

Several test simulations were also carried out to calibrate the control strategy. The result of the tests is summarized in Table 6.1, along with the summary of other scenarios.

All scenarios have to deliver the ventilation requirements of 6 liter per second per person which is supplied at 19 °C.

6.2.3 Results of BES-only simulation

6.2.3.1 Scenario 1: all-air system

Figure 6.6 shows the temperature predictions of all-air system scenario. The operative temperature is kept to maximum 24 °C during occupied period. The operative temperature in Figure 6.6, however, shows some values higher than 24 °C. This is because the controlled temperature is located in the middle (the centroid) of the zone. The MRT and the operative temperatures presented in Figure 6.6 (and also in the figures that follows) are from the location near the glass wall, where the MRT is expected to be higher than in the center of the zone.

Table 6.1 Scenarios for application study

Scenario	System	Control strategies
1	All-air	Operative temperature of zone air node is controlled at 24 °C
2	TACS, ceiling	Dry bulb temperature of zone air node is controlled at 23 °C
3	TACS, ceiling	Dry bulb temperature of ceiling internal surface temperature is controlled: 0500 – 0600: at 19 °C 0600 – 1900: free-float, maximum is kept at 22 °C 1900 – 0500: free-float

In this scenario, the heat is extracted directly from the center of the zone at the air point. To compensate the high radiation from the glass wall (which make the MRT as high as 28 °C), the air temperature is made very low to keep the operative temperature within the comfort level. The air temperature in the center of the zone is predicted as low as 21 °C.

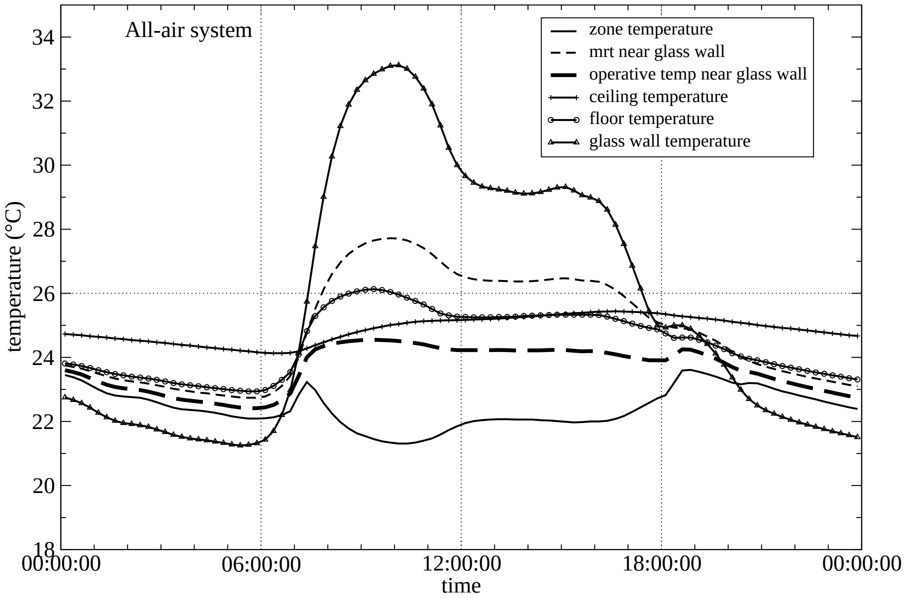


Figure 6.6 Temperature prediction for all-air system (no CFD simulation)

6.2.3.2 Scenario 2: TACS – controlled air node

Figure 6.7 shows the temperature predictions for TACS where the controlled variable is the room air temperature.

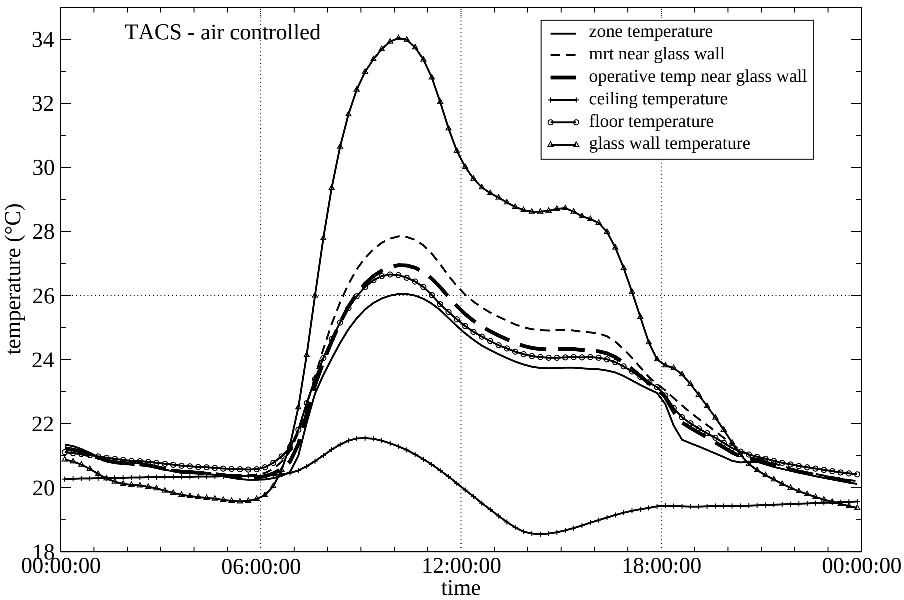


Figure 6.7 Temperature prediction for TACS with controlled air node (no CFD simulation)

The system is supposed to control the room air temperature at 23 °C. However, since heat is extracted from the concrete core of the ceiling, due to the high thermal mass the effect of the heat extraction on the room temperature is very slow. Moreover, the system cooling capacity is limited to 10kW because of the risk of condensation in the ceiling. Higher system capacity will make the surface temperature drops even lower that will increase the risk of condensation. These are the reason why the room air temperature fluctuates up to 26 °C.

The MRT values are influenced by the high temperatures of the glass wall and the floor. With the MRT values are up to 28 °C, the operative temperatures are outside the comfort range (above 26 °C) for around two hours.

6.2.3.3 Scenario 3: TACS – controlled surface node

This scenario introduces the new control scheme for the TACS. In the previous scenario, the supposedly controlled parameter (i.e. the room temperature) is in fact uncontrolled. Instead of trying to control the uncontrollable, this scenario changes the controlled parameter to the ceiling surface temperature. The strategy is to keep the ceiling surface temperature down to 19 °C several hours before the occupancy hours, and let the surface temperature to free-float (but limit to a maximum of 22 °C), and then release it to free-float without limit after occupancy hours.

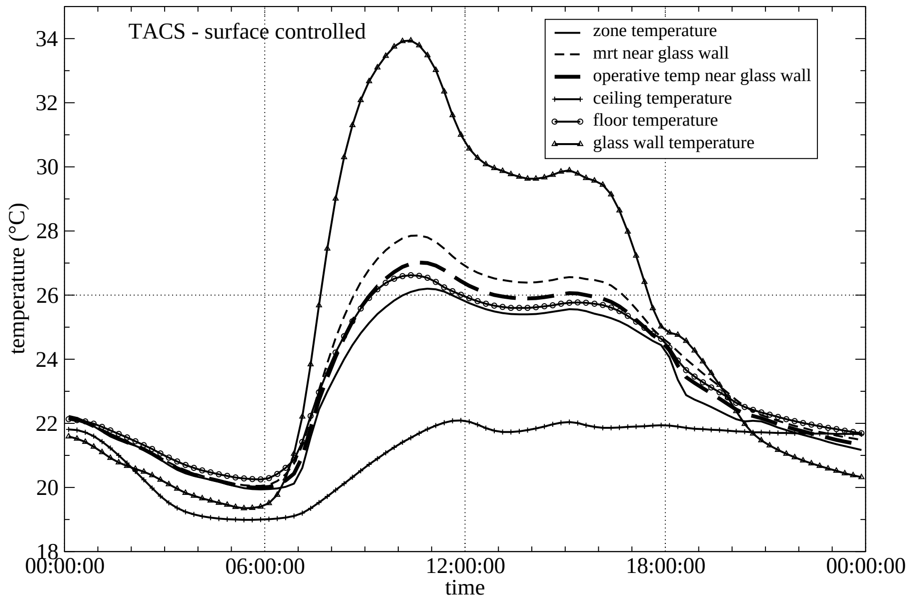


Figure 6.8 Temperature prediction for TACS with controlled surface node (no CFD simulation)

The result (Figure 6.8) shows that the air temperature reached slightly more than 26 °C. And with the high MRT values, the operative temperature exceeds the maximum value of 26 °C for around 3 hours before noon, and stays within the border for several hours before going down in late afternoon hours. The ceiling surface temperature shows a good indication of controllability, i.e. down to 19 °C before 06:00 and stays below and around 22 °C during occupancy period.

6.2.3.4 Comparison between scenarios

Energy demand

Figure 6.9 shows comparison of energy demands between scenarios. All scenarios have the same amount of energy to deliver the minimum ventilation requirements of 8.62 kWh. Scenario 1 has the lowest energy demand as it delivers the energy directly into the air point.

Scenario 2 demands the highest energy due to the unreliable control scheme. Scenario 3 with better control scheme shows significant reduction in energy demand of almost 20%. Scenario 3 demands 33% higher energy compared to Scenario 2.

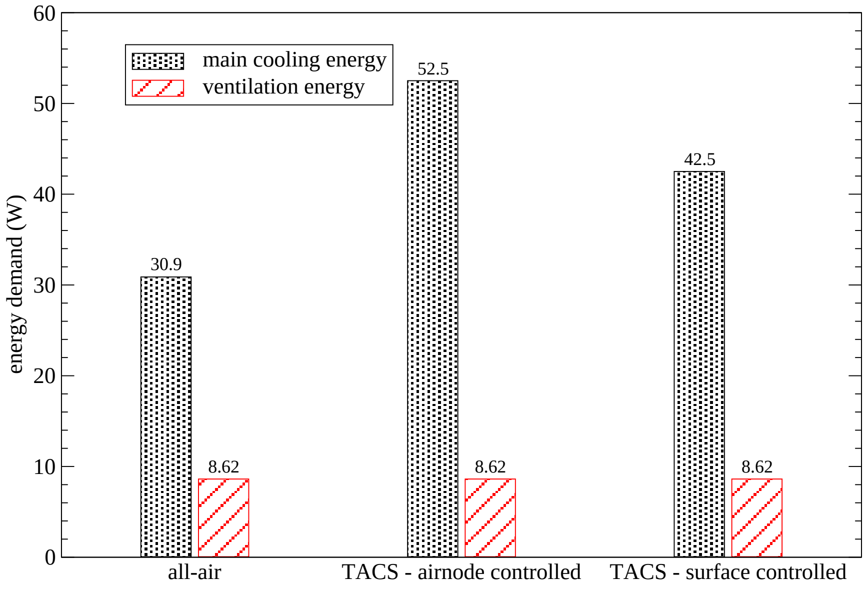


Figure 6.9 Comparison of energy demand between three scenarios

It is important to note that the above comparison is on the energy demand, not the energy consumption. The all-air system must take into account the high fan energy while for TACS the main cooling energy is transferred by water at much lower flow rate, which is more efficient. Furthermore, Scenario 3 introduces a control scheme where the cooling energy is consumed mainly outside occupancy hours, which is potentially on off-peak hours that have lower electricity price.

Risk of condensation

Figure 6.10 shows that Scenario 2 has a condensation risk for three hours in early afternoon. Scenario 3 on the other hand does not have any risk of condensation through out the day.

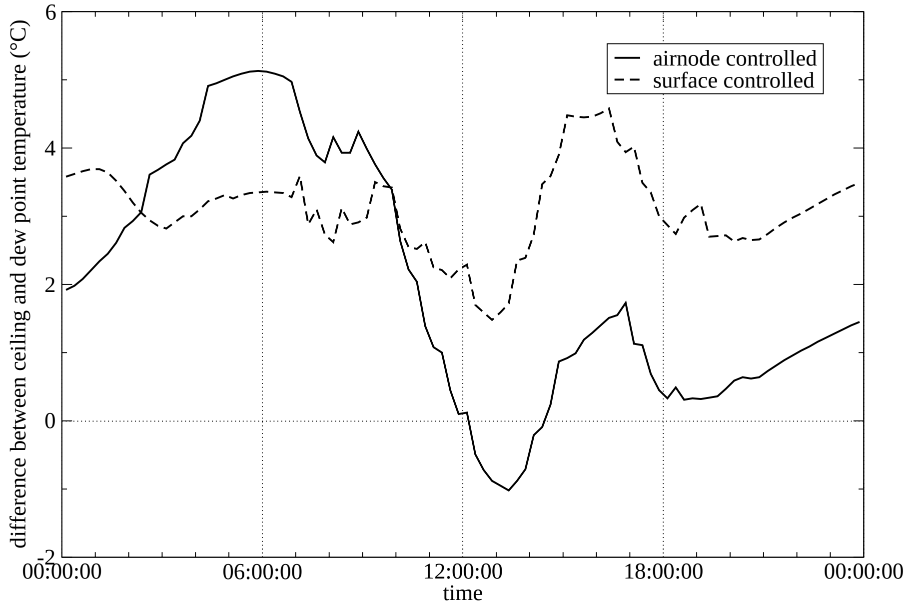


Figure 6.10 Possibility of condensation between scenarios 2 and 3

CHTC prediction

Figure 6.11 shows the prediction of CHTC between the 3 scenarios. In Scenario 1, the ceiling CHTC have a very low value around 0.25 W/m^{2}K. In Scenarios 2 and 3 the ceiling CHTC are higher up to around 2.8 W/m^{2}K. The floor and ceiling CHTC's are also below 2.8 W/m^{2}K.

6.2.4 Sensitivity analysis on CHTC

The guideline as proposed in Chapter 3 is used to assess the need for coupled simulation for this problem. The BES-only simulations were repeated to check the sensitivity of the problem to CHTC.

For every scenario, two simulations were carried out each using a low value and a high value of CHTC. The most relevant performance indicators to be used for this sensitivity analysis are the operative temperature and the energy demand.

Figure 6.12 shows the result of sensitivity analysis for operative temperature. Scenario 1 and 2 are not sensitive towards the CHTC value. However, Scenario 3 shows a degree of sensitivity (almost 2 °C difference between high and low CHTC). Furthermore, if 26 C of operative temperature is taken as the standard value, above which the condition would be deemed uncomfortable, then the coupled simulation is needed for Scenario 3 as the sensitivity results shows the difference between compliance and non-compliance to the standard.

Figure 6.13 shows the sensitivity analysis results for energy demand. All scenarios show a significant degree of sensitivity towards CHTC (with difference of energy demand of 26.9%, 24.6%, and 13.8% for Scenarios 1, 2, and 3 respectively). This significant degree of sensitivity justifies the use of coupled simulation.

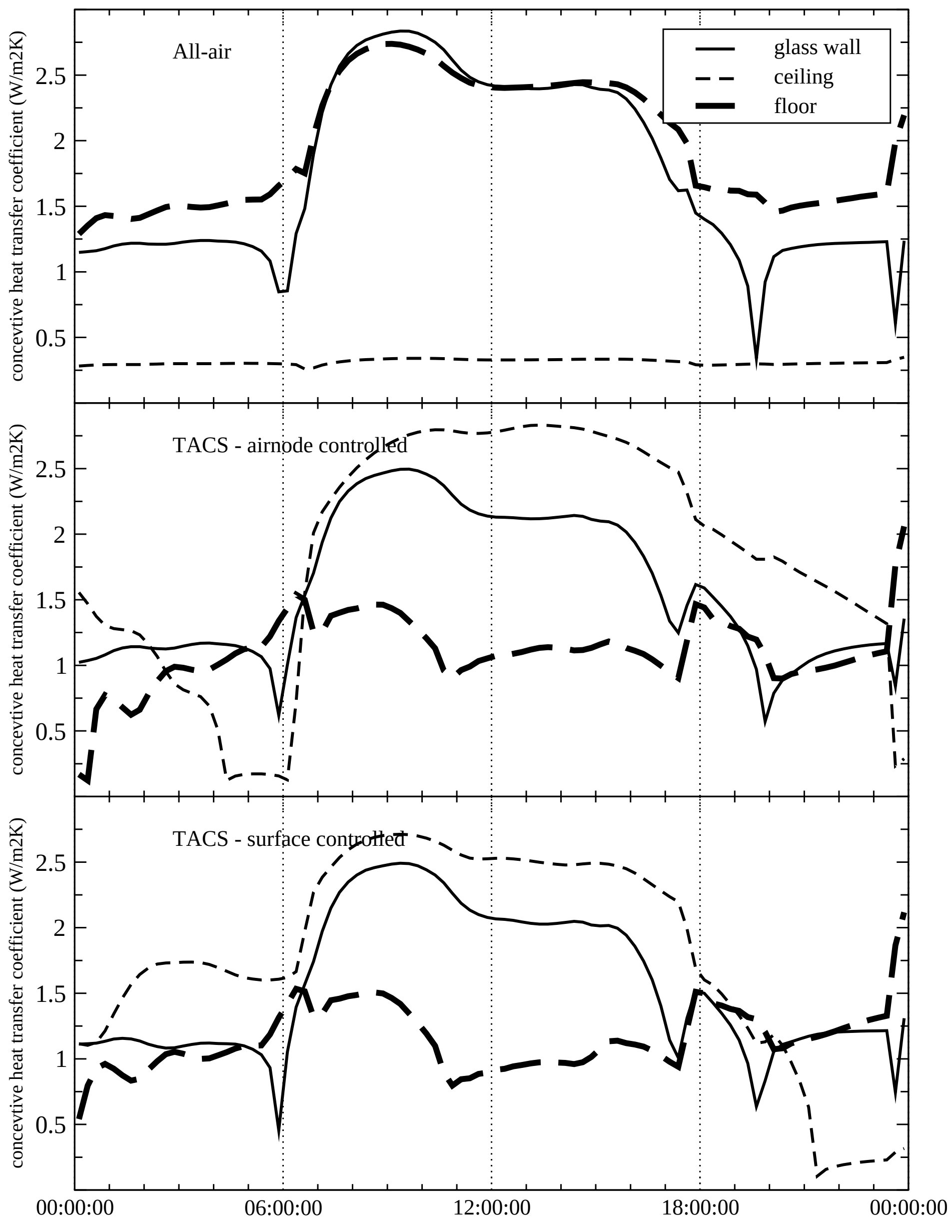


Figure 6.11 Comparison of CHTC prediction between scenarios

6.2.5 Potentials for coupled-simulation

There are two main issues that can be answered by coupled simulation: (1) the calculation of CHTC with regards to energy calculation and (2) the comfort calculation.

6.2.5.1 Calculation of CHTC

The CHTC of the ceiling on Scenarios 2 and 3 are lower compared to the values reported in the literature. The total heat transfer coefficient for cooled ceiling is between 9 – 11 W/m^{2}K (Stetiu 1998). The convective part can have the coefficient of 3.5 – 5.5 W/m^{2}K. The values shown in Figure 6.11 are considerably lower than that.

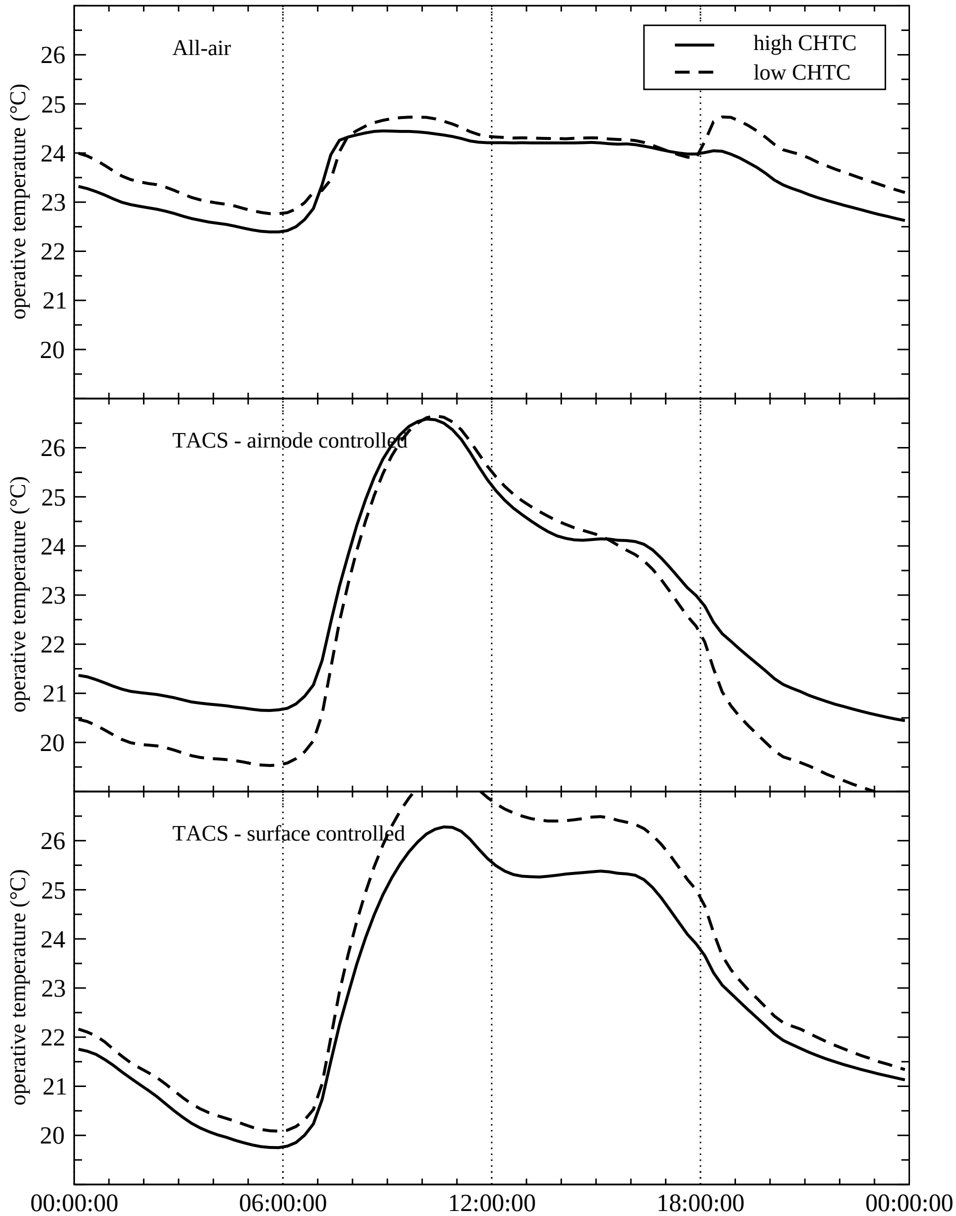


Figure 6.12 Sensitivity of operative temperature to CHTC

Furthermore, the CHTC value on the glass wall needs special attention. The displacement ventilation used in all the scenarios cause temperature stratification, which needs to be considered in the calculation on CHTC. The use of coupled BES-CFD simulation enables the effect of temperature stratification to be considered in the calculation.

6.2.5.2 Comfort calculation

The calculation of the correct surface temperature is very important for comfort calculation. It is even more important for radiant system which relies on surface temperature difference as the main mechanism for heat transfer. The correct calculation of CHTC certainly helps to achieve better comfort condition.

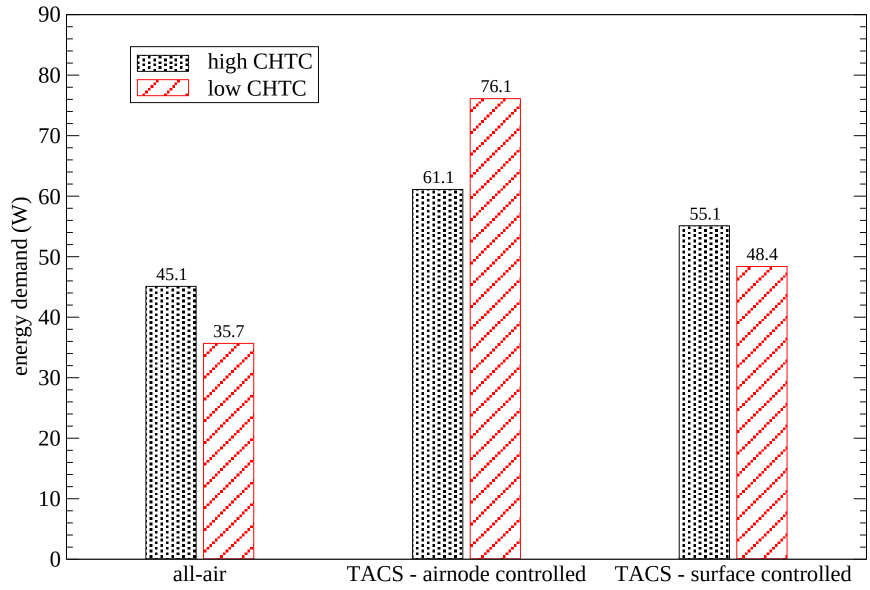


Figure 6.13 Sensitivity of energy demand to CHTC

The use of coupled BES- CFD simulation also enables the non-uniform temperature distribution to be considered in calculating the comfort condition. Comfort condition is a local condition, which should be assessed based on local values.

The calculation of operative temperatures as in previous sections shows a discrepancy. In one hand the MRT is a local value, on the other hand the air dry-bulb temperature is uniform throughout the space. This is contrary to the expected condition when displacement ventilation is used. The value of the air temperature in the lower parts of the room (where the MRT is measured) should be lower than what is presented in previous sections. With the result of CFD from the coupled simulation, the local air temperature anywhere in the room can be easily obtained.

6.2.6 BES-CFD coupled simulations

The CFD model (shown in Figure 6.1) includes the occupants and the desk. The heat flux from humans and equipments are defined by assuming 50% convective part. For the CFD simulations only convective heat transfer is considered, and radiation model is not activated. For simplicity, all the loads from equipments are defined as plane source at the desks. Only the CHTC of the walls were sent to BES while the CHTC on the human and desk surfaces were not.

Four displacement ventilation supplies are located near the floor, one on north and south side, and two on east sides. The two exhausts are located at the north and south wall near the top of the west glass wall.

As this CFD model is considerably more complex compared to the other CFD models that have been used in this thesis, the mesh is created using unstructured tetrahedral elements.

6.2.7 Results of coupled BES-CFD simulations

6.2.7.1 Scenario 1: all-air system

Figure 6.14 shows the temperature predictions of CFD-coupled simulation for all-air system scenario. The same control scheme was used as the uncoupled simulation, i.e. the operative temperature in the center of the zone was kept to maximum 24 °C during occupied period. The air temperature, MRT, and operative temperature presented in Figure 6.14, however, are from the area near the glass wall where the comfort problem is likely to occur. The results are similar with Figure 6.6 for this scenario.

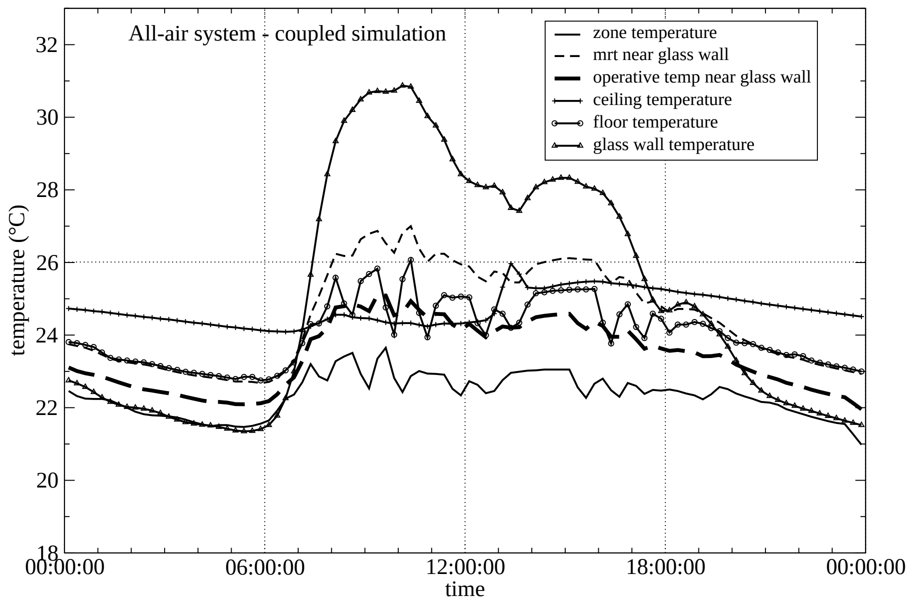


Figure 6.14 Temperature prediction for all-air system (CFD-coupled simulation)

The main difference can be shown for air temperature. The uncoupled simulation predicted around 1 °C lower during occupancy hours. This is because the uncoupled simulation assumes a well-mixed condition where the temperature of the whole space is represented by a single temperature. And this makes the simulation to predict lower air temperature to compensate the high MRT near the wall.

In the coupled simulation, however, the MRT and the zone temperature are taken from the same location near the wall. This makes the predicted air temperature to be a little bit higher while still maintaining the level of comfort.

6.2.7.2 Scenario 2: TACS – controlled air node

Figure 6.15 shows the coupled simulation results for scenario 2.

Uncoupled simulation (Figure 6.7) predicted uncomfortable condition during late morning hours where the operative temperature is more than 26 °C. The coupled simulation, however, shows that this scenario can meet the comfort criteria.

This is the advantage of the coupled simulation where the comfort criteria can be assessed based on local values in the room. Assessment of local values is made possible by the high resolution simulation like CFD.

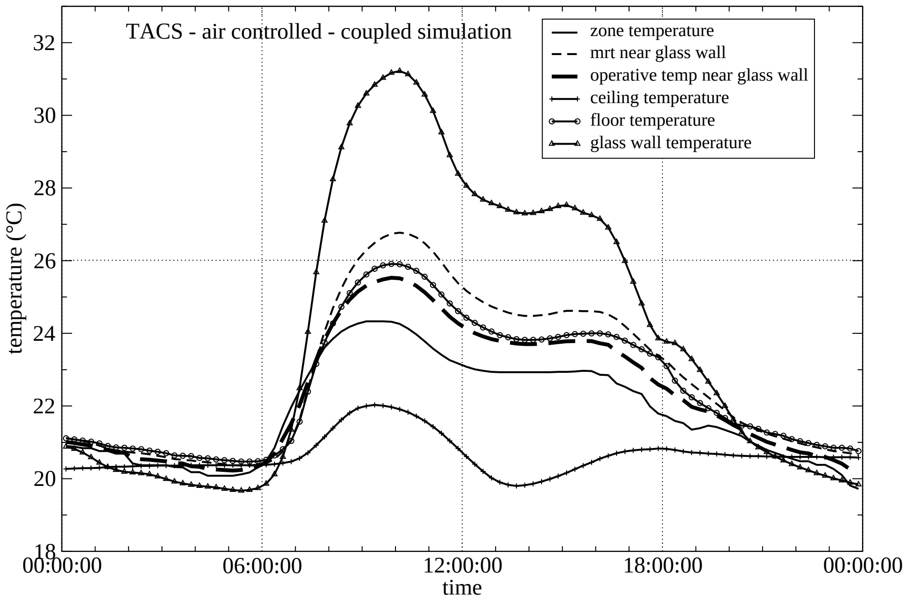


Figure 6.15 Temperature prediction for TACS with controlled air node (CFD-coupled simulation)

6.2.7.3 Scenario 3: TACS – controlled surface node

The same trend as Scenario 2 is also shown in the results for Scenario 3 (Figure 6.16). The comfort assessment using coupled simulation did not predict uncomfortable condition in the late morning hours as predicted by uncoupled simulation (Figure 6.8).

6.2.7.4 Comparison between scenarios

Energy Demand

Figure 6.17 shows comparison of energy demands between scenarios. As in uncoupled simulations, all scenarios have the same amount of energy to deliver for the minimum ventilation requirements (8.62 kWh).

Scenario 1, as in the uncoupled simulation, has the lowest energy demand. For TACS cases, Scenario 3 shows higher energy demands than Scenario 2 which is different from the uncoupled case where Scenario 3 had a lower energy demand. As shown in Figure 6.18, the coupled simulation results in an increase of energy demand for Scenario 3, while it causes a decrease for Scenario 2.

This trend is consistent with the sensitivity analysis carried out earlier in the calibration process. Scenario 3 had a decrease in energy demand when simulated using higher CHTC value, while Scenario 2 had an increase. The sensitivity analysis could only indicate the trend that a performance indicator is sensitive towards the CHTC value, but it could not predict what the actual difference is. The coupled simulation can quantify how much is the difference. This phenomena clearly shows the advantage of the coupled simulation, where a scenario thought earlier as having lower energy demand was then proved of having higher.

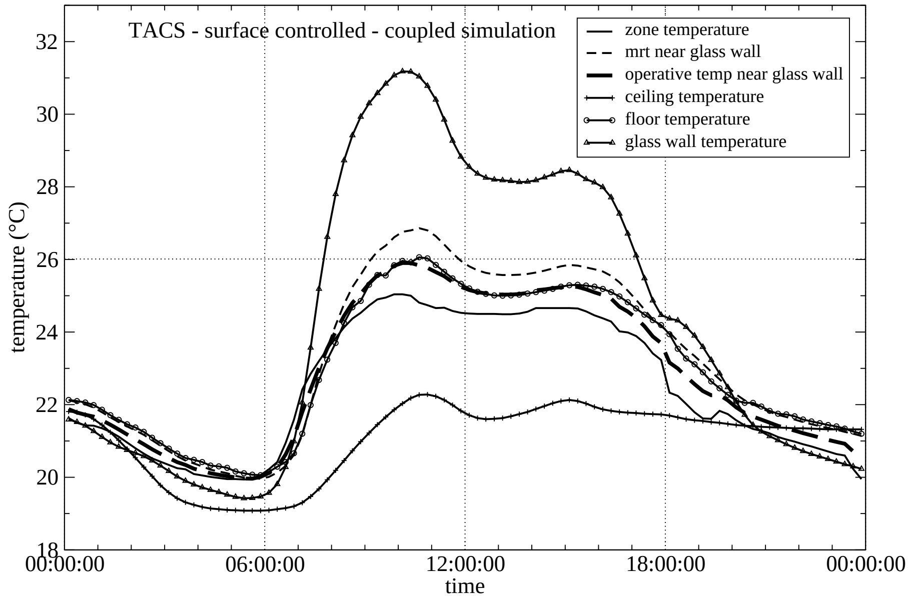


Figure 6.16 Temperature prediction for TACS with controlled surface node (CFD-coupled simulation)

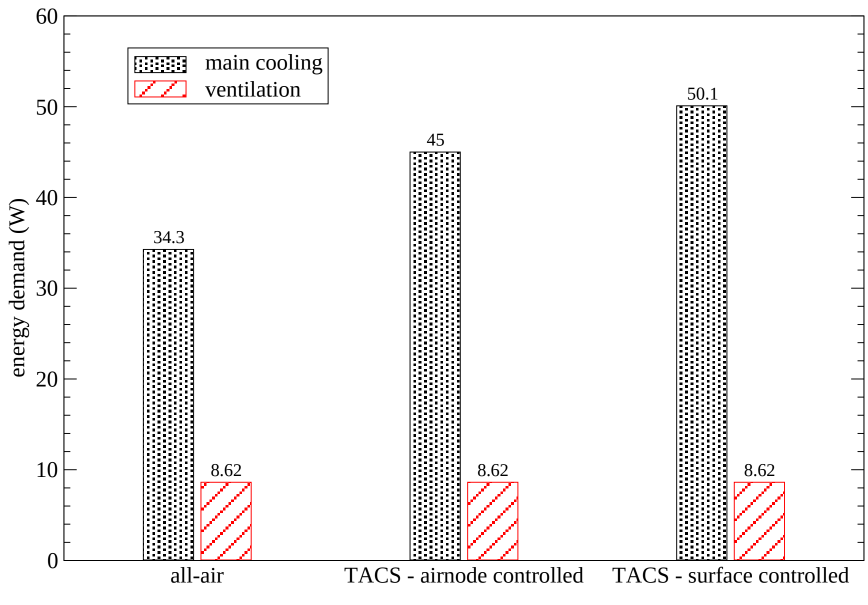


Figure 6.17 Comparison of energy demand between three scenarios (CFD-coupled simulation)

Risk of condensation

Figure 6.19 shows that both Scenarios 2 and 3 do not have condensation problem on the ceiling surface, which is different from what was predicted by the uncoupled simulation. The risk of condensation is greater in the early afternoon. The simulation shows Scenario 3 has a range of around 1.5 C to further decrease the surface temperature in the afternoon hours without a condensation problem.

However, if the surface temperature is decreased, it will potentially increase the energy demand.

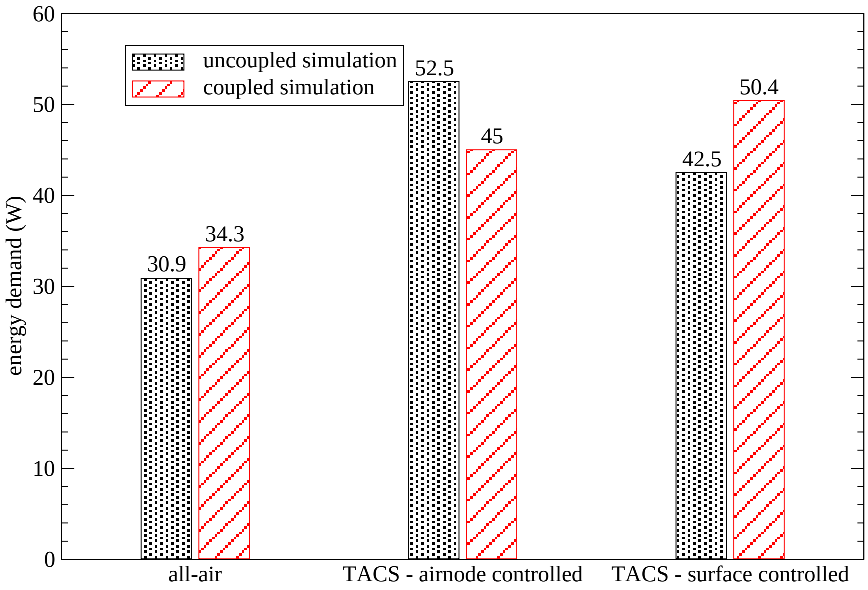


Figure 6.18 Comparison of energy demand between coupled and uncoupled simulations for three scenarios

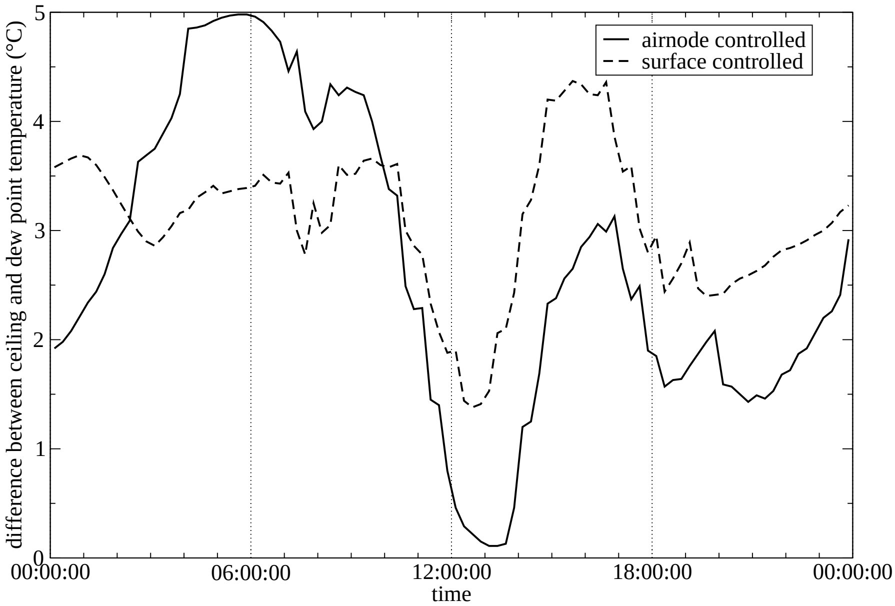


Figure 6.19 Possibility of condensation for scenarios 2 and 3 (CFD-coupled simulation)

CHTC prediction

Figure 6.20 shows the calculated CHTC for all scenarios. In general, all scenarios have increase in CHTC values, especially in occupancy period. For Scenario 1, the increase is large for ceiling, because the default calculation method for uncoupled simulation predicted very low values of CHTC (Figure 6.11). For coupled simulation, CHTC values are between 6 – 8 W/m^{2}K when the air conditioning system is on. In the afternoon hours, Scenario 1 predicted a negative value of CHTC, which means a reverse in the direction of heat transfer in the ceiling, as predicted by CFD. Such a reverse in the direction of heat transfer caused by temperature stratification in the room can only be predicted by the coupled simulation.

For TACS cases, both Scenario 2 and 3 show similar values of CHTC. The values are between 5.5 – 7.5 W/m^{2}K.

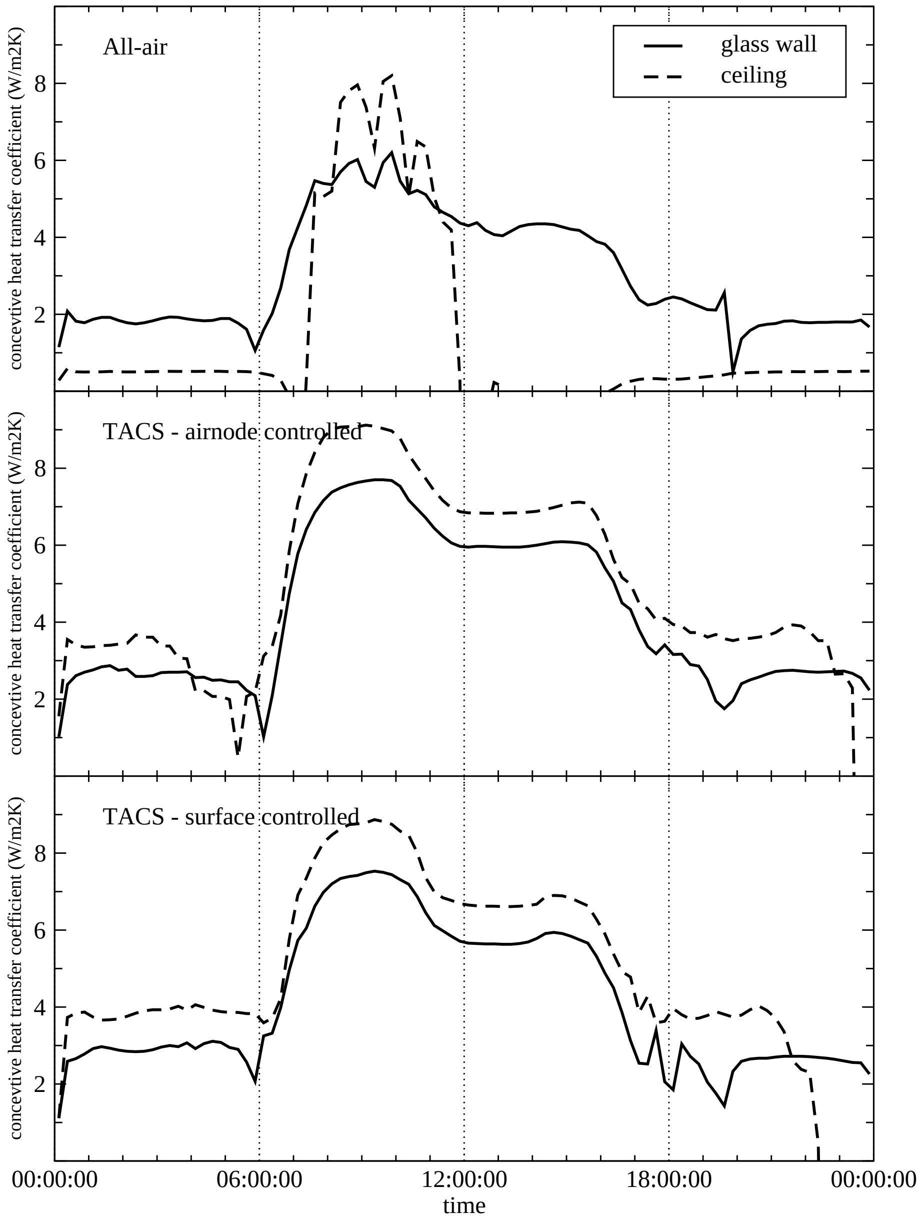


Figure 6.20 Comparison of CHTC prediction between scenarios (CFD-coupled simulation)

6.2.8 Conclusions

This application study has shown the application of external coupling to a design situation. The free-floating and uncoupled simulations were used to establish the basic knowledge on the behavior of the system. Then the guideline proposed in Chapter 3 was used to assess the need for coupled simulation. And finally based on the result of sensitivity analysis the couple simulations were carried out.

The main advantage of BES-CFD coupled simulation is the accurate calculation of CHTC. This chapter has shown how that main advantage can be utilized to simulate the TACS.

Accurate CHTC value is needed to calculate the correct surface temperature. The performance of the TACS system depends on the correct calculation of heat exchange on the surface and in the core of the concrete. And the surface temperature affects both energy and comfort performance of the TACS.

Furthermore, the high resolution of the CFD simulation makes it possible to assess the comfort level in the zone as a local parameter in a part of the room. Of course, CFD-only simulation will be able to do the same. However, with coupled simulation the dynamic of the comfort level throughout the day can be assessed, due to the availability of the surface temperature data.

Chapter 7

Conclusions

This section summarizes the findings of this study. The objectives set out in Chapter 1 are revisited and the findings are discussed in terms of these objectives. The second part of this chapter proposes recommendation for future works to further develop the external coupling method. The main theme of the recommendation is to introduce intelligence for the coupled procedure.

7.1 Concluding remarks

The ***first objective*** of this study is:

> *to generate guidelines with regard to the necessity or applicability of BES, CFD and the cooperative approach in terms of integrated design of buildings and systems. The findings in this line of work will become a basis to approach the implementation of external coupling.*

Chapter 3 has been devoted specifically to achieve this objective. A Coupling Procedure Decision Methodology (CPMD) has been developed to systematically assess the need for coupled simulation for any particular problem. The selection of which tool to use in a simulation work is usually left to the engineers to decide based on their subjective assessment.

The novelty in CPDM is that it shifts the decision making process from subjective assessment to objective assessment. CPDM covers the whole range of simulation tools and proposes a mechanism on how to select the appropriate tool according to the need at a specified time.

The CPDM uses the sensitivity analysis as the decision making tool to select the appropriate level of resolution for the simulation (do we need CFD simulation or not?) and the appropriate level of complexity (do we need coupled simulation or not? Or should we run BES-only simulation or CFD-only simulation?). Simulation analysis is proposed as the tool for decision making, however other mechanisms might also be possible and more work is needed to refine the decision criteria.

The ***second objective*** of this study is:

> *to develop a prototype of cooperative BES and CFD design environment for optimizations of building energy performance and indoor environment.*

Chapter 4 and 5 addressed this objective. Based on the literature, an external coupling mechanism was developed which can be summarized as follows:

1. Strategy: Quasy-steady dynamic coupling

   BES controls the time marching, and CFD simulations are in steady state.
2. BES Time step should 2 hr or less
3. CFD is invoked every time step in a user-specified time range
4. Exchanged data
   - i. BES-to-CFD:
     - o Wall temperatures
     - o Heat injection/extraction
   - ii. CFD-to-BES:
     - o CHTC

The above mechanism has been developed into a working prototype by taking ESP-r and Fluent as an example for implementation. A generic requirement has also been formulated so that the implementation can be repeated using other BES and CFD software.

An extensive validation study has also been presented. The study covers 3 cases, which represent natural convection flow and mixed convection flow, and also represent a room with radiator and a large room with mixing air conditioning system.

The validation study shows that the external coupling works well. From the BES point of view, the coupled simulation can provide a more accurate CHTC prediction, which directly affects the energy demand prediction. From CFD point of view, the coupled simulation can provide dynamic boundary conditions so that the changes in airflow patter throughout the simulation period can be observed.

The comparison with experimental results showed that the external coupling performed as good as the internal coupling.

At this point it is important to revisit the introduction to this thesis that discussed about the potentials of external coupling from the software development point of view. Even though the results are now comparably similar, the external coupling has a better chance to improve faster, especially on the developments of CFD packages. With the external coupling the latest development in CFD packages can be immediately available to the user once the communication protocol between BES and CFD has been implemented. On the other hand, with internal coupling, the same development in CFD will have to be implemented into the source code, which will take significantly much longer than the relatively simple plug-and-play method offered by the external coupling.

To put everything into perspective, it is also important to note that this thesis shows the advantage of external coupling in terms of solver capability and software maintenance. Other aspects of integrated simulation may (or may not) favour the internal coupling. One example is the control system action. However, this particular aspect is an on-going research that will be reported in the future (Yahiaoui et al. 2004).

7.2 Recommendations for future works: introducing intelligence

Below are two recommendations for future works. Both recommendations emphasize the direction of coupled simulation research towards intelligent coupling mechanism.

7.2.1 Decision making criteria for the guideline

The guideline proposed in Chapter 3 has introduced a systematic method to approach the coupled simulation. The guideline however does not intend to fully automate the decision process. The main reasons are:

1. that the sensitivity analysis is still done manually, and
2. the criteria to select which performance indicators are important (the weight that is put to a certain performance indicator) and what is the significant sensitivity for that particular performance indicator (is 20% deviation from the base case significant?) are still not well formulated.

Very recent developments have opened the opportunity to further develop the guideline. The sensitivity analysis is already been used as part of simulation study to assess the uncertainty of a particular problem (Macdonald 2002). Furthermore, new developments have resulted in a new method for quantification of performance indicators (e.g. Augenbroe and Park 2005).

With these two recent developments, further development of the guideline proposed in Chapter 3 can be started. This will be a step stone toward an intelligent coupled simulation.

7.2.2 Selective CFD invocation

7.2.2.1 Background

In various implementations of coupled simulation between CFD and BES, the CFD is usually invoked at a predetermined time step, which is specified by the user. There are two drawbacks with this approach:

1. The user can only have a broad estimate on when CFD simulation is needed. There is no checking mechanism for this estimation.
2. Within the time range specified, the CFD simulation will be invoked, regardless whether it is really needed or not. This will lead to inefficiency in terms of computing resource.

A solution to this problem is to develop a checking mechanism so that the coupling controller can make its own decision whether to call CFD or not. This can be implemented as follows:

1. The history of boundary conditions (i.e. wall temperature) is kept in a database. On every time step the new boundary conditions are checked against the database. If the boundary conditions are relatively the same as any of the data in the history, CFD will not be invoked.
2. Gopher CFD simulation (i.e. CFD simulation with a very coarse grid) is used to estimate the similarity of the air flow with any of the data in the history. This will make use the non-dimensional numbers.
3. Only if the two checks above conclude that the flow is really different, then the (full) CFD run will be invoked.

7.2.2.2 Case description

This section uses the IEA Annex 26 Atrium for the case to show the usefulness of selective invocation of CFD simulation in a coupled simulation. The air conditioning system capacity was increased to supply more air so that the forced convection in some surfaces can be more obvious, so that the room can have all possible combination of natural convection, mixed convection and forced convection in the room throughout the simulation period.

7.2.2.3 Capabilities of gopher run

Gopher run is selected as the tool to decide whether the room air flow pattern has changed significantly. As gopher run is supposed to be simple and fast, it is both interesting and important to establish confidence whether the coarse mesh used by the gopher run is actually capable of predicting the correct air flow classification.

A test was carried out to study whether the gopher run is capable to predict the correct airflow classification. Three meshes with different coarseness are used as summarized in Table 7.1. All three models are used to simulate 10 days of spring condition with a time step of 1 hour. In total there are 240 CFD simulations as the CFD is called for every time step.

Table 7.1 Summary of the performance test for gopher run capabilities

Model	Mesh	Simulation time
Coarse	9x6x6	00:51:24
Fine	9x11x11	01:26:31
Full-CFD	35x23x23	18:43:46

Figure 7.1 shows the Grashoff Number (Gr) prediction for 10 days of simulation for south wall. As explained earlier in Chapter 4, this number used to classify the air flow regime on surfaces whether it is natural or forced or mixed convection. The full-CFD results should be taken as the standard “true” value, and the capability of gopher runs (fine or coarse mesh) is measured by how close their predictions are with the full-CFD prediction.

From Figure 7.1, the worst prediction happened on 8-Apr. Figure 7.2 shows the Gr prediction on 8-Apr, where there are 6 time steps where the gopher runs predicts different types of flow on the south wall.

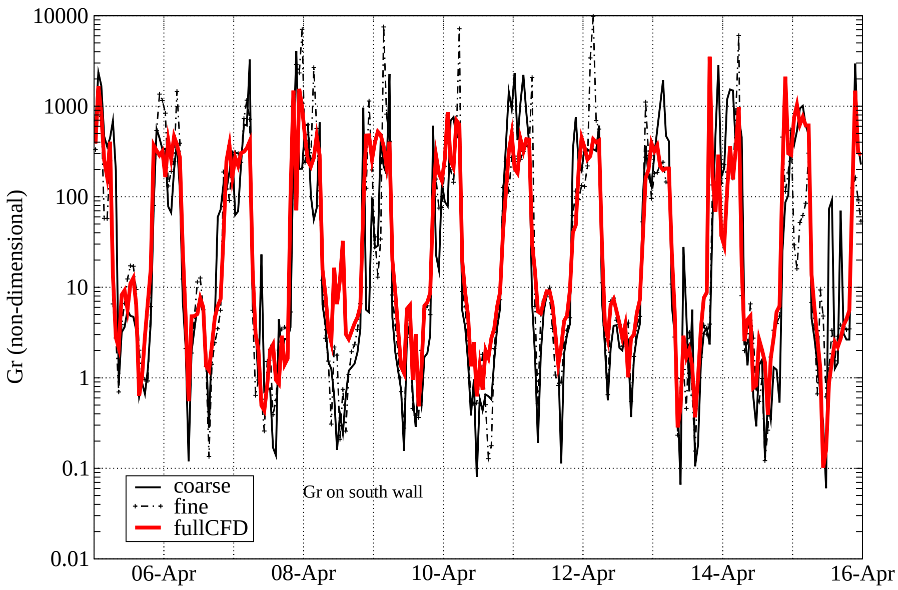


Figure 7.1 Grashoff Number prediction for 10 days

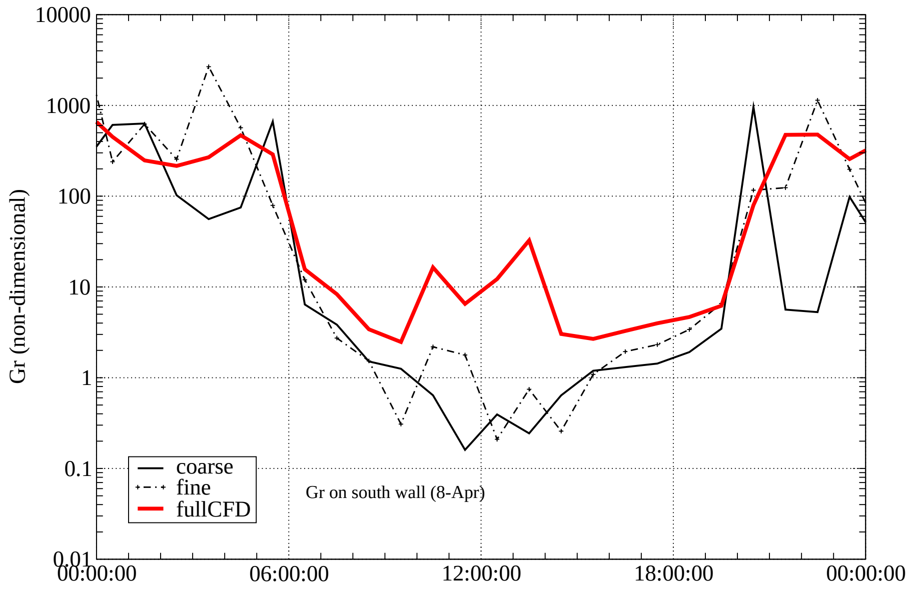


Figure 7.2 Grashoff Number prediction for 8-Apr

However, a closer observation shows that the false classification as it happened in Figure 7.2 "only" results in more CFD simulation, as it will flag a warning that there is flow pattern change so that the CFD simulation is needed. There is no instance of more devastating mistake where the gopher run flags a warning that there is no pattern change (while actually there is) so that the CFD is not invoked. The kind of mistake as happened in Figure 7.2, despite contrary to the objective of gopher run, is still acceptable to happen occasionally.

There are two important things to note on this study. Firstly, the scenario as it was used in the IEA Annex 26 experiment is so simple that the whole story can be contained in a mesh of 9x6x6. More complex scenario, i.e. more number of supply or exhaust openings, occupants in the space, furniture, etc, will need more cells to define. The idea of gopher run is to reduce the number of cell to the minimum as the case permits, but this study cannot offer any guideline as to what is the number of cells to be used as it is very case dependent.

Secondly, because of the mesh simplification, there could be another level of sophistication in model definition that should not have been used if the mesh is not reduced. In this example, the definition of supply openings for the gopher run is more complex than the full-CFD. The gopher run has very big cells so that the area of the opening is large, and this will make the momentum very low if the mass flow rate is fixed to the correct value. A momentum source needs to be defined in the cell next to the supply opening to give enough momentum so that the gopher run can predict the same throw pattern in front of the supply as the full-CFD. Another case with more complex scenario will face another level of difficulties than this.

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Propositions

Propositions associated with the thesis

External coupling between building energy simulation and computational fluid dynamics

1. The external coupling method shows better performance than the internal coupling in terms of solver capability and software maintenance.

    This thesis

2. The decision to use a certain simulation tool for a particular problem should not be tool-led. It should be problem-led.

    This thesis, Chapter 3.

3. A chain is only as strong as its weakest link. The idea of providing empirical correlations of convective heat transfer coefficient for building energy simulation is only as useful as the number of empirical correlations implemented in the program and the way they are implemented.

    This thesis, Chapter 4 and 5.

4. The new knowledge does not invalidate the old; and we employ it not for its greater sophistication but only, if at all, when it works better than the simpler model.

    Launder and Spalding in their lecture on turbulence model, commenting on the century-old mixing length hypothesis which becomes the basis of many simple turbulence models, including the one used in this thesis.

    Launder, B. E., Spalding, D.B. 1972. Lectures in Mathematical Models of Turbulence, Academic Press, London.

5. If sacrifice of simplicity and economy does not bring tangible benefits by way of greater accuracy and width of applicability, then the model may be referred back to its originator for further development

    Launder, B. E., Spalding, D.B. 1972. Lectures in Mathematical Models of Turbulence, Academic Press, London.

6. The amount of time spent for a task in a PhD research has no correlation with the number of pages used to report the task in the thesis. The work for many months can be reported in a few lines because the detail is not relevant to the thesis, while the work of a few weeks can become one chapter in the thesis. One of the daunting tasks of a PhD candidate is to focus on the important part of the thesis without being drifted into working something unnecessary.

    Hensen, J.L.M., my PhD supervisor, as he frequently reminded me.

7. Language comes before thought. For people without hearing disabilities, this is hard to believe, as it is taken for granted that we are born with the ability to think. But in fact, we cannot think if we do not have a language to reconstruct facts into meaning. We need a language to move beyond the concrete facts into the realm of ideas. This is why deaf babies have a high risk of mental retardation if they are not introduced to a language that does not need a sound to convey. As Sacks put it: “...to be defective in language, for a human being, is one of the most desperate of calamities, for it is only through language that we enter fully into our human estate and culture, communicate freely with our fellows, acquire and share information. If we cannot do this, we will be bizarrely disabled and cut off—whatever our desires, or endeavors, or native capacities”.

    Sacks, O. 1990. Seeing voices: a journey into the world of the deaf, HarperPerenniel, New York.

8. In research, as indeed in everyday life, very often we have of necessity to decide our course of action on personal judgment based on taste. Only the technicalities of research are "scientific" in the sense of being purely objective and rational. Paradoxical as it may at first appear, the truth is that, as W. H. George* has said, scientific research is an art, not a science.

    Beveridge, W. I. 1936. The art of scientific investigation.

    * George, W. H. 1936. The Scientist in Action. A Scientific Study of his Methods. Williams & Norgate Ltd., London.

9. The danger of scientific myopia can be described very clearly in the anonymous definition of PhD research: doing a deep-and-deeper study in a narrow-and-narrower field until reaching a point where you know everything about nothing.

10. Teaching is nothing like the art of painting, where, by the ***addition*** of material to a surface, an image is synthetically produced, but more like the art of sculpture, where, by the ***subtraction*** of material, an image already locked in the stone is enabled to emerge.

    Gatto, J. T. 2002. Dumbing us down: the hidden curriculum of compulsory education, 2nd edition, New Society Publishers, Gabriola Island, BC, Canada.

Curriculum vitae

Ery Djunaedy is actually my given name. As many other Indonesians, I do not have surname nor family name. But since I lived outside Indonesia, I started to use my last name as my family name.

I was born in Lhokseumawe, North Aceh, in Aceh Province of Indonesia. But being an Acehneese, a nation proud of its migrating culture, I actually never lived in Aceh. I went to three primary schools in two cities, two junior high schools in two cities, and managed to hold on to only one high school. In the first twenty years of my life, I have already lived in five different cities as far apart as London and Helsinki. In between I also managed to master three different local languages, though I still cannot speak fluent Dutch after 4 years living there.

I got my basic degree (Sarjana Teknik, ST) in 1995 from the Department of Engineering Physics, Institut Teknologi Bandung (ITB), Indonesia. I did my final year project in the Building Physics Lab in the department. I fell in love with building physics, and have never turned my attention to any other field of study. I also fell in love with a woman during my final years at the university. I managed to get a marriage certificate before I got my ST diploma.

I worked one year as Building Maintenance Engineer in Matahari Dept. Stores in Jakarta, Indonesia, with main task of developing maintenance program for the stores. I resigned after the maintenance program was running well.

I continued my study in 1997 at the National University of Singapore (NUS). I did the MSc on a part-time basis, while at the same time working as Research Assistant in the Indoor Air Quality Lab, Dept. of Building, NUS. I entered the world of building performance simulation in my involvement in the research project that uses Computational Fluid Dynamics to simulate the indoor air environment. I started to write papers to be published both in conferences and scientific journals. I got my MSc(Building Science) degree in 2000, three years after I set foot in Singapore, after completing my MSc dissertation on diffuser modeling for CFD. I stayed for another year in Singapore to complete the research project I was assisting.

In May 2001, I started the PhD research at the Technische Universiteit Eindhoven. I managed to complete this research ten days before the four-years-appointment as PhD candidate ends. This thesis you are now reading is the report of the research.

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Previous research has shown that building is a complex system whose behaviour can only be understood by taking into account its dynamic interactions. Optimizing the building (and its sub-systems) as a whole is not the same as optimizing the subsystems or components separately, because the latter would miss the dynamic interactions between the subsystems. The research direction in the area of building performance simulation has then moved towards an integrated multi-domain building simulation tools.

This thesis shows the viability of the external coupling method in achieving the integrated multi-domain building simulation tools. Different from the internal coupling method where the domain expansion always means writing new codes into the existing program, the external coupling combines two or more programs during run time. Using the external coupling method, the code changing can be kept to minimum and the development in any domain can be made available to other domains immediately, provided the communication protocol between the domains has been established.

Considering the importance of building energy simulation (BES) in the building design process and the current trend of wide-spread use of computational fluid dynamics (CFD) simulations, these two domains were selected as the basis of the work in this thesis. The coupling procedure developed involves the two (BES and CFD) domains.

This thesis proposes a guideline to assess the necessity of coupled simulation. Sensitivity analysis is used a tool in the guideline to select the appropriate complexity and resolution of the simulations. This guideline considers the whole range of available tools and defines logical steps on how to select the appropriate tool for a certain problem. Although it was (initially) developed for airflow domain, this guideline can also be applied to any domain.

This thesis also implements the external coupling method using a specific BES and CFD package, and specifies the general requirements so that the implementation can be repeated using any BES and CFD programs. A validation study was conducted as a quality assurance measure, and an application study was carried out to show the feasibility and usability of the external coupling method.

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