

TOWARDS THE APPLICATION OF DISTRIBUTED SIMULATION IN HAM ENGINEERING

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ABSTRACT

This paper presents ongoing research about an integrated approach to perform high resolution heat, air and moisture (HAM) simulation of whole buildings. There are several HAM modelling tools, with different space and time resolution. The integrated approach establishes run-time external coupling of existing tools (building envelope HAM, BES, CFD) and utilizes the capabilities of one tool in an attempt to compensate the deficiencies of the other. The paper presents the literature review of approaches for domain integration, the physical processes as dealt with by existing tools, coupling requirements and it addresses the importance of validation and coupling necessity decision procedures.

INTRODUCTION

Building simulation can be potentially applied to analyse important building performance aspects such as thermal comfort, mold growth and condensation (Crawley et al. 2008). The uncertainty associated with such simulations can be high, and incorrect simulation results can lead to design with adverse effects on health, comfort and functionality of space, which in turn might lead to unwanted extra cost (Mudary et al. 2007). In some cases, high resolution simulations are needed for heat, air and moisture (HAM) transfer to obtain more accurate results. Such high resolution simulation of whole buildings might require coupling of different geometrical and physical domains which involves the exchange of variables on time-step basis. In whole building HAM modelling, we focus on three geometrical domains: exterior, building envelope and interior, and three physical domains: heat, air and moisture.

In recent years, the use of building performance simulation (BPS) tools to predict and analyze the HAM behavior of buildings has grown significantly (Hens, 2005, Tariku et al. 2006, Woloszyn et al. 2008). These tools can be classified into three groups: Computational Fluid Dynamics (CFD), e.g. Fluent,

CFX; building envelope HAM tools (BEHAM), e.g. HAMFEM, Delphin, CHAMPS, WUFI, Match, hygIRC; and finally Building Energy Simulation (BES), e.g. ESP-r, EnergyPlus. These tools often focus on a specific geometrical domain in combination with one or more physical domains. Furthermore, they have strong capabilities but also some particular deficiencies in terms of boundary conditions, physical models and resolution in space and time. For instance, the existing advanced BEHAM tools perform HAM transfer simulations in the building envelope, generally driven by fixed or simplified boundary conditions. Detailed HAM modelling of the building interior and exterior is possible with Computational Fluid Dynamics (CFD) models. In CFD however, the implementation of meteorological boundary conditions is significantly less advanced than in Building Energy Simulation (BES). BES is mainly used to assess the thermal performance of buildings during the entire year. It is a powerful tool, but it generally includes simplified air flow, heat and moisture transfer modelling, when compared to BEHAM tools or CFD.

This paper presents ongoing research about an integrated approach to perform comprehensive HAM simulations for whole buildings including all geometrical and physical domains. To the knowledge of the authors, such integration has not been performed previously in the literature. The paper briefly discusses the main topics involved in the ongoing research and presents its first results: approaches for domain integration, relevant physical processes, interface variables, coupling requirements and validation. Finally the coupling necessity decision procedure is demonstrated, which intends to indicate the necessary simulation resolution level to answer a given design question.

APPROACHES FOR DOMAIN INTEGRATION

In buildings, a complex interaction of HAM transfer processes between the external environment, the building envelope and the indoor air environment

occurs. Optimum performance cannot be achieved unless the building itself is considered as a whole (Hensen 1991, Clarke 2001). In recent years, there have been considerable efforts in order to integrate different physical and geometrical domains to obtain high quality results. These integrations can be classified in two different types. The first type is the development of a single BES tool to include different domains (internal coupling); the second type is the use of external run-time coupling between different tools with BES tools (external coupling). These two approaches and their respective state of the art are explained below.

Internal coupling of domains with BES tools

This approach is the traditional way of expanding a BES tool. It implies expanding the BES code by adding missing part inside it (Figure 1 - left). Internal coupling has been used in many research projects. This coupling strategy involves background research, development of a pilot program, validation of the tool etc. (Mayer et al. 1982). Therefore this strategy in the development of a BES tool is time-consuming, expensive and the final numerical tool might still lack certain aspects in terms of modelling of physical processes.

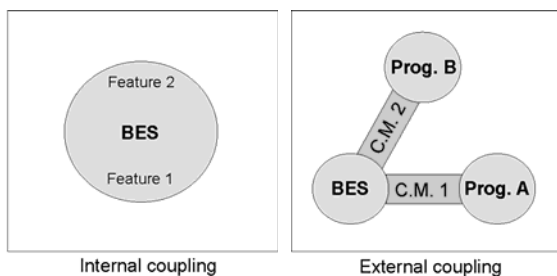


Figure 1 Internal coupling versus external coupling

Internal coupling of BES tools with CFD has been implemented and investigated for indoor air climate with different degrees of complexity in several research efforts (Beausoleil-Morrison 2000, Srebric et al. 2000, Zhai 2003). There are some other models which have taken into account moisture for studying indoor air quality issues (e.g. Amissah 2005). Although some works include all physical and geometrical domains, they may face some restrictions due to internal coupling implementation which offers limited options and features.

External coupling of domains with BES tools

Figure 1 (right) shows an alternative way for developing a tool in which external run-time coupling of different tools is adopted. By this approach existing

tools work in parallel and exchange data on a time-step basis (e.g. Trcka et al. 2006). In this approach, instead of rewriting and recompiling the code in order to add more features to the tool, external run-time coupling of different tools is established. External coupling not only eliminates the disadvantages mentioned in the previous section, but also yields a final tool that is more flexible for further development. In other words, the effort of expanding a specific tool in missing features is substituted by writing a much simpler code which handles the coupling mechanism (CM) between one tool (e.g. BES) and another tool (e.g. CFD) which has those features already implemented and validated (Figure 1 - right).

By adopting this method, BES can use existing numerical tools which are already coded and validated. In one of the most recent works using domain integration, an external coupling between BES and CFD using ESP-r and FLUENT was performed (Djunaedy et al. 2005). This prototype included heat and air as physical domains and the building interior and the building envelope as geometrical domains.

PHYSICAL PROCESSES

The complexity of the real world is high, and models cannot describe all existing physical processes and scales. In engineering, a good model should be as simple as possible, including only the relevant processes that are necessary to provide a reliable answer to the design questions. Therefore, selecting the physical processes to be included in a new model is a key task, which defines its main capabilities and constraints. For each geometrical domain, the following sections present the relevant physical processes that are considered in this research, needed for whole building HAM simulation.

EXTERIOR

Several exterior physical processes are currently modelled in BES and BEHAM tools with a high level of detail, such as: short-wave direct and diffuse radiation, long-wave radiation, etc.

On the other hand, wind-related physical processes in the exterior domain, such as convective heat and mass transfer, wind-driven rain, ventilation and infiltration are often only included in a simplified way in current BES and BEHAM tools. Those physical processes are incorporated using simplified databases or empirical models that sometimes ignore important aspects, such as the building geometry, the approaching wind profile or the sheltering effects by neighbouring buildings. The impact of those wind-related physical processes in BPS is discussed in the next sections.

Convection

The importance of convection on the external building facade is described by (e.g. Spitler et al. 1991, Lomas 1996, Palyvos 2008). A simple approach to model this physical process is the use of a combined radiant and convective transfer coefficient. In this case, the physical description might be quite poor, because the radiant heat exchange is often calculated based on the air temperature, instead of the temperature of the sky, surrounding buildings and ground. Therefore several tools adopt separate coefficients for each physical process. The common approach in BES and BEHAM tools is the use of empirical correlations to calculate the external convective heat transfer coefficient. The uncertainty in the current methods is enhanced because the results of many of those empirical models are not in agreement with each other, indicating that some aspects of the physical process are missing. Besides, from basic studies in heat transfer, it is known that the object shape plays a decisive role in the convective heat transfer. It should not be different in the built environment, and this presents a reasonable justification to include convection in this ongoing research.

For convective mass transfer, often a similar level of simplification is applied, and the current practice is to use the Lewis analogy between heat and mass transfer (e.g. Janssen et al. 2007). This analogy is valid under specific conditions which cannot be always found in building applications (Derome 1999). Even when the analogy is valid, the mass transfer calculation is based on heat transfer coefficients which can have a high uncertainty associated with themselves. Therefore, the mass transfer may present high uncertainty as well. CFD has been used to study convection on external building surfaces (Blocken et al. 2009) and has shown to give very accurate results, although it is very computationally demanding.

Wind-driven rain

Wind-driven rain is an important boundary condition in HAM calculations (Blocken et al. 2004, 2007, Janssen et al. 2007). Blocken et al. (2007) successfully validated CFD simulations to predict the catch ratios at the building facade, indicating that this methodology is ready to play its role in whole-building simulation. Catch ratio charts exist for simplified building geometries, such as isolated cubes. When this data is applied for a complex building geometry, such as an L-shape building, the uncertainty will be much higher due to the lack of geometrical similarity. The aim of the current ongoing research is to use catch ratios calculated for the precise building geometry, avoiding the use of simplified databases. Future research in this

area will take into account other important rain related physical processes, like splashing and run-off (Abuku et al. 2009).

Infiltration, Ventilation and air related HAM effects

Infiltration and ventilation rates are important parameters for whole-building performance. Using coupled BES and air flow network (AFN) models, de Wit (2001) describes the wind pressure as one of the main sources of uncertainty in BPS. Wind pressure is also an important boundary condition in the combined HAM transfer in the building envelope. Hagentoft (1996) provides an example of how air flows in the building envelope can significantly affect the overall heat and moisture transport. Based on those facts, the wind pressure on building facades is one of the physical processes that is important to be taken into account in the current ongoing research. The current methods to take into account the wind pressure are: empirical data for simplified geometries and simplified analytical methods. An overview is given in (Cóstola et al. 2009). In both cases the building geometry is restricted to simple shapes such as parallelepiped buildings, in a situation similar to those described in the previous sections. Also in this case, good quality CFD presents a viable alternative to the current methods and can be applied to almost any arbitrary geometry.

BUILDING ENVELOPE

The combined heat, air and moisture transfer in the building envelope is a strongly coupled physical process (Janssen et al. 2007), which has been studied for many years. The features of BEHAM tools are not under analysis here, but rather how to combine the BEHAM tools with the other tools to perform whole-building simulation. Here, our main concern is not the physical process, but the overlap of domains in the three kinds of tools: BES, BEHAM and CFD. All three tools can perform transient heat calculation in the solid domain, but only one should be used in the coupled simulation. It is generally assumed that BEHAM tools are the best option to perform the calculation in the building envelope, which means that the envelope heat transfer code in the BES tools should be deactivated. This action affects the heart of BES tools, and presents one of the biggest challenges in this ongoing research.

INTERIOR

The building interior is the space enclosed by the building envelope. The building interior has its main interface with the building envelope, by convection. However, the building interior also interacts with the

building exterior through large openings, and with HVAC systems through air inlets and exhausts, etc. Large openings and HVAC are not addressed in this ongoing research. Concerning convection, as the exterior domain, several tools still adopt combined convective-radiant transfer coefficients, while others adopt separate fixed transfer coefficients for convection and radiation. State of the art BES tools include a wide range of empirical correlations for convective transfer coefficients. Recent research demonstrates the potential of coupled BES-CFD to calculate convective heat transfer in the building interior (Djunaedy et al. 2005). Other points which demand further studies are the integration with AFN and air-based HVAC systems. In this paper, we assume that BES tools include AFN. A list of those BES tools are provided in (Crawley et al. 2008)

COUPLING REQUIREMENTS

Before moving to the coupling between BES and other numerical tools, the close interaction of geometrical and physical domains should be studied. Table 1 presents the first result of the analysis on this issue. This table is divided into three main parts: exterior, building envelope and interior. For each of these geometrical domains, the physical processes mentioned before and also the variables and their coupling status are described.

Table 1 Coupling and decoupling status of the variables for the whole building HAM simulation

Exterior		
Physical process	Variables	Coupling and decoupling status
Ventilation	C_p	Decoupled
Convection	h_{ext} & $h_{m,ext}$	Decoupled (Assuming forced convection)
Wind-driven rain	η	Decoupled (Assuming no splashing or run-off)
Building envelope		
Heat and mass transfer	T & p_c	Coupled + Domain synchronization
Interior		
Convection	h_{int} & $h_{m,int}$	Coupled

For the exterior domain, ventilation and the general term “convection” lead to pressure coefficients C_p and the convective transfer coefficients for heat and mass (h_{ext} and $h_{m,ext}$). In this ongoing research, it is assumed that most of the time there is no feedback sensed by C_p from the building envelope and interior domain, so a decoupled solution is considered for this variable. The dominating factors in the exterior convective heat transfer coefficients are wind speed, wind attack angle,

surface to air temperature, building geometry etc. At low local wind speeds, surface to air temperature differences initiate a buoyant flow in the vicinity of the building surfaces and consequently can play an important role in the prediction of the heat transfer coefficient. When the local wind speed is higher than a certain value, the effects of temperature difference on the air flow around the building can become negligible. The value associated with the transition from natural to forced convection might be represented by $U_{Threshold}$. A coupled solution should be applied for local wind speed values lower than $U_{Threshold}$, but in this paper we are assuming a dominating forced convection condition for the exterior domain which means a decoupled solution will be applied.

Assuming the Lewis analogy between heat and mass transfer in this regard, the same situation might apply for the convective mass transfer coefficient ($h_{m,ext}$). The catch ratio (η) is a parameter that defines the intensity of wind-driven rain (WDR). It is a complex function of space and time (Blocken et al. 2004). In this paper, we assume that η can be determined via a decoupled solution. This assumption might be valid when some local physical processes are neglected, such as splashing, film forming and run-off. Variables dominating heat and moisture transfer through building envelopes are temperature (T) and capillary pressure (p_c), which are strongly coupled in the domain. Considering the prevailing range of indoor air flow regimes in the indoor environment, interior transfer coefficients (h_{int} & $h_{m,int}$) are coupled with the building envelope state such as interior surface temperature and relative humidity.

For the coupled solutions, quasi-steady dynamic coupling (non-iterative approach) has been chosen as the coupling mechanism in this ongoing research due to its effectiveness (Zhai 2003, Djunaedy et al. 2005).

VALIDATION

Validation can be defined as “the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” (AIAA 1998). In the current ongoing research, the coupled software will use higher-level physical models, which include more terms to describe the physical processes. These models should provide a closer description of the reality, but in order to prove this hypothesis, benchmark data are necessary. Detailed experimental work of HAM whole-building behaviour is very complex and out of the scope of this ongoing research. An alternative approach is inter-model comparison between BES and

BEHAM tools when compared to general purpose CFD tools (Mirsadeghi et al. 2008).

Whole-building HAM performance could, in theory, be studied in CFD tools. This approach would be computationally very expensive due to time scale differences between fluid and solid, and it should also be validated. However, it is possible to run and validate simple models, such as the convection in a cube and use it to test the coupled prototype. For this ongoing research the simple model will be a small cube with solid porous walls and moist interior air. The cube will be submitted to step functions in the boundaries, and the simulation results from CFD will be considered as the benchmark for the comparison with: the BES-BEHAM-CFD full prototype, the stand-alone BES, the BES-BEHAM coupling, and the BES-CFD coupling. Based on the comparison, the deviation on the prediction for those tools will be calculated for this case, and the expected result should demonstrate that the full prototype has the minimum deviation.

The inter-model comparison explained above intends to show that the coupled prototype provides a more accurate calculation for this specific simple case. Therefore, it does not yield full information on the accuracy of the full coupled prototype when used in other cases. Realistic cases covering the range of applications for the tool would be necessary to assess the model accuracy.

In this section, the plans for the model validation were briefly presented. However, the validation concept also demands the agreement between the model accuracy and its adequacy for an intended use. The concept of accuracy is treated in the next section.

ACCURACY AND UNCERTAINTY

In the definition of validation provided in the previous section, the term “accurate” is not defined. In metrology “accuracy is a qualitative concept” (ISO 1993). It agrees with the definition of validation in ERCOFTAC (2000): “Validation is the process of ensuring that the CFD model being solved is a good representation of the real world”, where “good” is clearly a qualitative concept, which depends on expert judgement. In this research, we adopt the uncertainty concept, which is quantitative, to judge the quality of the simulation results.

In metrology, uncertainty is defined as “a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand” (ISO, 1993). The definition focuses the efforts on “the measurement result and its evaluated uncertainty rather

than on the unknowable quantities ‘true’ value and error” (ISO 1993). It assumes that the true value, as well as the error, is never known, and the answer for any measurement is described by an interval where one could expect the real value exists. A similar definition is used in this paper for BPS, where the uncertainty in simulation is defined as: a parameter, associated with the result of the simulation that characterizes the dispersion of the values that could reasonably be expected around the true value of the simulated quantity. This definition is different from the usual one adopted by the CFD community, where uncertainty can be defined as “A potential deficiency in any phase or activity of the modeling process that is due to the lack of knowledge” (AIAA 1998). The metrological definition does not enclose the sources of “potential deficiencies”, but rather focuses on the probability that the true value lies in a certain range, where “probability is viewed as a measure of the degree of belief that an event will occur” (ISO 1993). For the purpose of this paper, particularly the work described in the next section, the metrological definition is more suitable, because it allows an evaluation of the reliability, or degree of belief, in the simulation results. There are several sources of uncertainty in the simulation. Most of the previous research about uncertainty in BPS is focused on the input parameters uncertainty, like the work of de Wit (2001). In the framework of this ongoing research the attention is focused on the modelling uncertainties. This uncertainty mainly originates from “simplification of equation”, as it is named by ERCOFTAC (2000). In several cases, it is clear that the equations implemented in BPS are far from the state of the art description of the physical process. The simplifications described in section related to physical processes in this paper, are good examples of this practice. When state-of-the-art physical models are adopted, the remaining modelling uncertainty is only the one due to lack of knowledge about the physical processes (AIAA 1998). The point to be addressed consists of defining the level of simplification in the simulation that is acceptable to answer a given design question. The means to define the correct modelling level, which is a topic that is described in the next section.

COUPLING NECESSITY DECISION PROCEDURE

Building performance simulation (BPS), includes a very large range of applications, for different building typologies, geometries, climates, etc. Those tools are used to predict several performance indicators (PI). For each specific case, the accuracy required will be different and it depends on economical, technological

and social constraints from designers, contractors and final users. In order to meet the accuracy requirements, computer simulations of physical processes can be performed with different levels of complexity and resolution, leading to different uncertainties in the calculation. The coupled prototype tool to be developed in this research intends to reduce the uncertainty in the prediction of some PI for buildings, but in several cases the stand-alone models can perform a reliable simulation, even considering their uncertainties. Therefore there is a need for a procedure which helps the model users to choose an appropriate level of complexity and resolution. Previous work in this field can be found in Djunaedy et al. (2005), but only limited to heat and air in the study of convection in the internal geometrical domain. The procedure proposed here is designed to be applicable for all the domains and physical processes involved in this research. This procedure is called the Coupling Necessity Decision Procedure (CNDP). The overall concept used in the CNDP is presented below, and then a preliminary example is provided. CNDP is based on uncertainty analysis and on target values for the PI under study. Figure 2 outlines the structure of the CNDP.

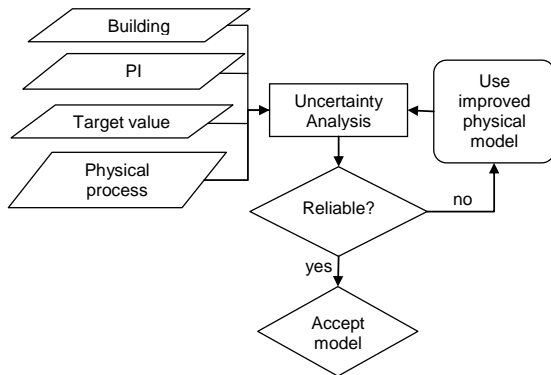


Figure 2 CNDP structure

CNDP indicates the use of successive increments in the modelling level and in each step the uncertainty is compared to the target value, such as maximum or minimum allowed values. This process is repeated until the uncertainty in the results does not compromise the designer judgement. When this level is achieved, the model is accepted and no further refinements are necessary. In the following paragraphs, the use of CNDP is exemplified for convection at the external facade, using the software ESP-r. This example presents the preliminary result on the CNDP development, and the some of the main barriers to its implementation are described.

The building under study is a 3 storey building, with dimensions of 10 (m) × 10 (m) × 10 (m). The internal loads, operation, construction and other configurations are based on the BESTEST settings (Judkoff et al. 1995). In this case, the PI addressed in the simulation is the annual cooling energy demand. The target value for the annual cooling energy demand in this example is the arbitrary maximum value of 20 kWh/m², which leads to 6 MWh for the whole building. Target values are normally found in standard, building regulations or in guidelines for sustainable building, such as the HK-BEAM, BREEAM and LEED certifications (Lee et al. 2008). Cases with no target value are not addressed in this paper. Once the building, physical process, PI and target value are set, the modelling refinement can be initiated. The simplest way to model convection at the external facade is the use of combined convective-radiant transfer coefficients. In ESP-r, those two physical processes are treated separately by default, so this lower level of simplification is not considered here. The second approximation is the use of fixed values for the convective heat transfer coefficient. Based on literature review of experimental results, the range of possible values is constructed. Figure 3 presents the results for simulations using different values for h_{ext} . In this case, the uncertainty compromises the designer judgement, because there is a risk that the building presents a value for this PI that is higher than the maximum allowed value. In this case, a higher level model should be used to address this physical process.

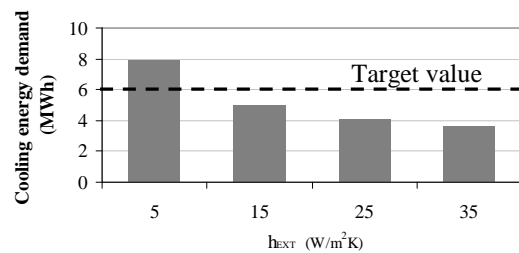


Figure 3 Uncertainty on h_{ext} using fixed values

The next possibility is the use of empirical correlations, as a more complex model. In many BES tools, empirical correlations represent the state of the art, however they only provide a deterministic output, with no uncertainty. The lack of knowledge about the uncertainty in the current methods is one of the challenges to be faced in the present research. Without this information, it is not possible to judge the adequacy of the simulation for this PI and target value. Recovering the discussion from the previous sections, the definition of validation is related to the uncertainty and the intended use, so choosing the correct

modelling level can be understood as the final step in the validation of the simulation.

In this paper, another method is used in order to overcome the lack of information about the uncertainty when using empirical correlations. There are a large number of empirical correlations for this physical process, which are based on different experimental results. Considering this situation, the proposed method assesses the uncertainty of this modelling technique by the comparison of the results using several different correlations, as presented in Figure 4. As can be observed, there is still a large variation in predicted energy cooling demands. Reasonably, these large deviations originate from the particularities in h_{ext} predictions by different correlations. However, the cooling load is below the target value in all cases. So, even in a highly uncertain scenario the simulation can be considered valid, because it predicts the PI value and there is no risk that the target value will be exceeded. In this case, there is no need of using higher level modelling techniques, like CFD simulations. One of the drawbacks of this approach is that the model user will have to carry out simulations using several different empirical correlations.

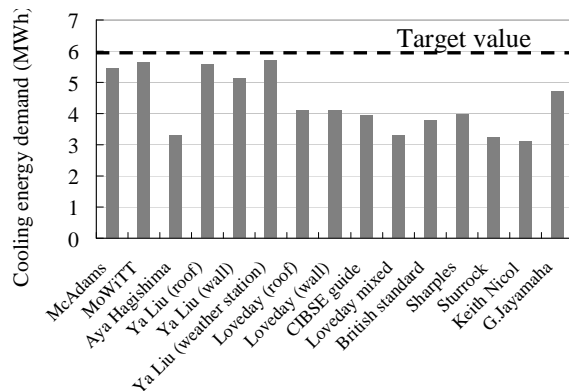


Figure 4 Estimation of cooling demand using different h_{ext} correlations

Another drawback is the risk that all the empirical correlations show the same deficiency when describing one specific building. In this case the uncertainty analysis shown in Figure 4 will not be valid.

The next step of the current research will address these deficiencies related to uncertainty calculation in the CNDP. It is important to stress that this analysis might be time-consuming. Some efforts were done in the past to automate uncertainty analysis, focused on some input variables (Macdonald 2002).

CONCLUSION

A non-exhaustive review of an integrated approach towards comprehensive HAM simulations for whole buildings has been presented. The need for a new tool for coupled HAM simulations, the methodology of its development, verification of the coupling mechanisms and the determination of its usability for different situations were described. In the whole-building approach, different physical and geometrical domains were considered. Then different physical processes, interface variables and their coupling status were discussed concisely.

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REFERENCES

- Abuku, M., Janssen, H., Poesen, J., Roels, S. 2009. Impact, absorption and evaporation of raindrops on building facades, *Build. Environ.* 44, 113-124.
- AIAA. 1998. Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. AIAA G-077.
- Amisshah, P. K. 2005. Indoor air quality-combining air humidity with construction moisture, PhD Thesis, Energy Systems Research Unit, Dept. of Mechanical Engineering, University of Strathclyde, Glasgow, UK.
- Beausoleil-Morrison, I. 2000. The Adaptive Coupling of Heat and Air Flow Modelling Within Dynamic Whole-Building Simulation, PhD Thesis, Energy Systems Research Unit, Dept. of Mechanical Engineering, University of Strathclyde, Glasgow, UK.
- Blocken, B., Carmeliet, J. 2004. A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics* 92(13), 1079-1130.
- Blocken, B., Carmeliet, J. 2007. Validation of CFD simulations of wind-driven rain on a low-rise building façade, *Build. Environ.* 42, 2530-2548.
- Blocken, B., Defraeye, T., Derome, D., Carmeliet, J. 2009. High-resolution CFD simulations for forced convective heat transfer coefficients at the facade of a low-rise building, *Build. Environ.* 44, 2396-2412.

- Clarke, J. A. 2001. Energy simulation in building design, 2nd edn, Oxford: Butterworth-Heinemann.
- Cóstola, D., Blocken, B., Hensen, J. L. M. 2009. Overview of pressure coefficient data in building energy simulation and airflow network programs, *Build. Environ.* 44, 2027-2036.
- Crawley, D. B., Hand, J. W., Kummert, M., Griffith, B. T. 2008. Contrasting the capabilities of building energy performance simulation programs, *Build. Environ.* 43, 661-673.
- Derome, D. 1999. Moisture occurrence in roof assemblies containing moisture storing insulation and its impact on the durability of building envelope, PhD thesis, Concordia University, Montreal, Quebec, Canada
- de Wit, M.S. 2001. Uncertainty in predictions of thermal comfort in building, PhD Thesis, Delft University of Technology, the Netherlands.
- Djunaedy, E., Hensen, J. L. M., Loomans, M. 2005. External coupling between CFD and energy simulation: implementation and validation, *ASHRAE Transactions* 111, no.1, 612-624.
- ERCRAFTAC, 2000. Best Practices Guidelines for Industrial Computational Fluid Dynamics, V. 1.0.
- Hagentoft, C. 1996. Heat, air and moisture transfer in insulated envelope parts: Performance and Practice. International Energy Agency, Annex 24. Final Report, vol. 1. Leuven: Acco.
- Hens, H. 2005. Annex 41 - Whole building heat, air and moisture response, AIVC 26th conference, Brussels, Belgium, 21-23 September.
- Hensen, J. L. M. 1991. On Thermal Interaction of Building Structure and Heating and Ventilating System, PhD thesis, Eindhoven University of Technology, Eindhoven, the Netherlands.
- ISO. 1993. Guide to the expression of uncertainty in measurements, ISO, Switzerland: ISO.
- Janssen, H., Blocken, B., Carmeliet, J. 2007. Conservative modelling of the moisture and heat transfer in building components under atmospheric excitation, *Int. J. Heat Mass Transfer*, 50 (5-6), 1128-1140.
- Judkoff, R., Neymark, J. 1995. International Energy Agency building energy simulation test (BESTEST) and diagnostic method. Report NREL/TP-472-6231. Golden: NREL.
- Lee, W.L., Burnett, J. 2008. Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED, *Build. Environ.* 43, 1882-1891.
- Lomas, K. J. 1996. The U.K. applicability study: an evaluation of thermal simulation programs for passive solar house design, *Build. Environ.* 31, 197-206.
- Macdonald, I. A. 2002. Quantifying the Effects of Uncertainty in Building Simulation, PhD Thesis, University of Strathclyde, ScotlandUK.
- Mavyer, T. W., Ellis, J. 1982. Implementation of an energy model within a multi-disciplinary practice, Proceedings of the CAD82, Brighton, UK.
- Mirsadeghi, M., Blocken, B., Hensen, J.L.M. 2008. Validation of external BES-CFD coupling by inter-model comparison, Proceedings of 29th AIVC Conference, Kyoto, Japan.
- Mudary, D., Fisk, W. J. 2007. Public health and economic impact of dampness and mold, *Indoor Air* 17, 226-235.
- NPARC Alliance CFD Verification and Validation, <http://www.grc.nasa.gov/WWW/wind/valid/tutorial/val assess.html>, (Retrieved on 25/02/ 2009. ERCRAFTAC.
- Palyvos, J.A. 2008. A survey of wind convection coefficient correlations for building envelope energy systems' modeling, *Applied Thermal Engineering* 28, 801-808.
- Spitler, J. D., Pedersen, C. O., Fisher, D. E. 1991. Interior Convective Heat Transfer in Buildings with Large Ventilative Flow Rates, *ASHRAE Transactions* 97, 505-515.
- Srebric, J., Chen, Q., Glicksman, L. R. 2000. A coupled airflow and energy simulation program for indoor thermal environmental studies, *ASHRAE Transactions* 106, 465-476.
- Strachan, P.A., Kokogiannakis, G., Macdonald, I.A. 2008. History and development of validation with the ESP-r simulation program., *Build. Environ.* 43, 601-609.
- Tariku, F., Kumaran, K., Fazio, P. 2006. Whole building heat and moisture analysis, IEA ANNEX 41 meeting, Lyon.
- Trcka (Radosevic), M., Hensen, J. & Wijsman, A. 2006. Distributed building performance simulation - a novel approach to overcome legacy code limitations, *Int. Journal of HVAC&R Research* 12, no. 3a, 621-640.
- Woloszyn, M., Rode, C. 2008. IEA ECBCS Annex 41 Final report - Volume 1: Modelling Principles and Common Exercises.
- Zhai, Z. 2003. Developing an integrated design tool by coupling building energy simulation and computational fluid dynamics, PhD thesis, Dept. of Architecture, Massachusetts Institute of Technology, USA.