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LITERATURE REVIEW AND RESEARCH NEEDS TO COUPLE BUILDING ENERGY AND AIRFLOW SIMULATION

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ABSTRACT

We have conducted a comprehensive literature review on motivations and methods for linking computational fluid dynamics (CFD) to building energy simulation (BES). The review begins with a focused evaluation on where and why a coupled simulation capability is needed. We then summarize methods for exchanging information, data, and model output between the CFD and BES tools, and comment on the suitability and performance of various data exchange strategies. We follow this with a review of possible software architectures employed for data exchange. Finally, we present typical use cases for the coupled simulation, and discuss critical research gaps for the coupled simulation.

Keywords: CFD; BES; Integrated Simulation.

1. INTRODUCTION

Due to the assumptions associated with simple multizone airflow models that are employed in typical BESs, most BES software may not provide satisfactory results for some applications. For instance, EnergyPlus, a common BES software, may not perform well in predicting localized comfort, the contaminate distribution within an occupant zone, or the control of HVAC systems (Crawley, Hand et al. 2008). In addition, multizone airflow models are often not suitable to simulate non-uniform airflow distribution within a zone, such as flow for displacement and natural ventilation. Moreover, it is challenging for a BES software to predict the correct convective heat transfer coefficient (CHTC). Most BESs estimate the CHTC with empirical formulas assuming the room air in room is instantaneously mixed. As shown by (Lomas 1996), the difference between the estimated annual heating energy using four different empirical formulas could differ by as much as 27%. These potential limitations of BESs may be overcome using CFD methods.

On the other hand, the CFD also has its own technical limitations. The CFD usually uses idealized static boundary conditions, such as fixed supply airflow rate and temperature, fixed wall temperature or heat flux through the wall. However, the actual boundary conditions are changing with weather condition and operation schedule of HVAC system that must be obtained from a BES (Djunaedy, Hensen et al. 2003).

As a result, it is possible to couple the BES and the CFD to provide missing information when a single program is not sufficient. This report reviews literatures on coupling the CFD with BES. The objective is to summarize the state-of-art research methods and provide guidance for the future research.

2. EXCHANGED DATA

This section is to summarize methods that have been reported to exchange information, data, and model predictions between BES and CFD tools, and discussed the benefits of the resulting simulation performance.

The information commonly transferred from a BES to a CFD include interior surface temperature of walls (Zhai, Chen et al. 2002; Zhang, Lam et al. 2012), boundary conditions at openings, including outdoor airflow velocity, pressure and temperature(Wang and Wong 2008; Ohba and Lun 2010), heat flux or air-conditioning load (Zhai, Chen et al. 2002; Fan and Ito 2012), supply airflow rate, temperature, humidity or pressure at supply diffuser (Ascione, Bellia et al. 2012; Fan and Ito 2012), and temperature or pressure at the outlet (Ascione, Bellia et al. 2012; Fan and Ito 2012). The possible information that may be transferred from the CFD to BES include: Indoor temperature distribution (Zhai, Chen et al. 2002; Ascione, Bellia et al. 2012), CHTC (Rong, Da et al. 2011; Zhang, Lam et al. 2012), flow rate through the openings, such as window, doors, outlet of the atrium (Wang and Wong 2008; Pan, Li et al. 2010; Zhang, Lam et al. 2012), and concentration of pollutants (Wang and Chen 2008; Goldsworthy 2012).

The selection of exchanged data can also impact the convergence, stability and computing speed of the coupled simulation. As concluded by Zhai and Chen (2005), sending the enclosure interior surface temperature from BES to the CFD and return the CHTC and indoor air temperature gradients to the BES can significantly improve the accuracy of the simulation.

3. DATA SYNCHRONIZATION STRATEGIES

We divide the strategies for data synchronization between the CFD and BES into three major categories, and describe them in subsection 3.1 to 3.3.

3.1. Static Synchronization Strategy

In the static coupling strategy the CFD exchanges data with the BES for only a few times, whether manually or automatically, in two methods: one-way and two-way exchange.

One-way static synchronization

The BES transfers data to the CFD at some specific time. Figure 1 shows the workflow of one-way static synchronization. The rectangle represents CFD and the ellipse represents the BES. The BES runs continuously while the CFD runs and receives the data only at a few moments. Since the CFD needs significantly more computing time than the BES, the one-way static synchronization can greatly reduce the total simulation time of a coupled simulation (Zhai, Chen et al. 2002). This method can be used when two programs are somewhat insensitive to the timing and the amount of exchanged data.

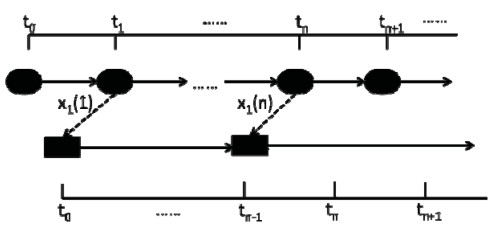

Figure 1 One-way static synchronization

Two-way static synchronization

The major difference between the one-way static synchronization and the two-way static synchronization (Figure 2) is that the later also sends the output of CFD to the BES (Zhai, Chen et al. 2002). The "feed-back/feed-forward" exchange is conducted in order to update the CHTC in the BES if it is significantly different from that calculated by the CFD.

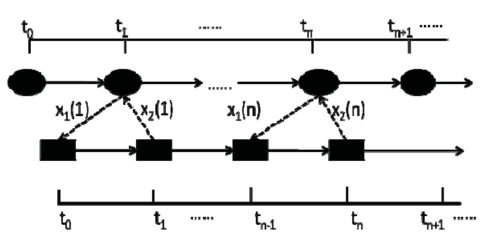

Figure 2 Two-way static synchronization

3.2. Dynamic Synchronization Strategy

By dynamic synchronization strategies two programs exchange data with each other at each predefined time step which indicates the communication frequency. Dynamic synchronization strategy exchanges data more frequently than the static ones so that the data synchronization typically has to been implemented automatically. We can further divide the dynamic synchronization into quasi-dynamic synchronization and full-dynamic synchronization.

Quasi-dynamic synchronization strategy

Quasi-dynamic synchronization (Zhai, Chen et al. 2002) is also called loose coupling (Trcka, Wetter et al. 2007) or "ping pong" coupling (Trcka and Hensen 2006). It requires the two programs to conduct one exchange of data at every time step. The quasi-dynamic strategy has two sub-categories: loose quasi-dynamic strategy and cross quasi-dynamic strategy (Trčka, Hensen et al. 2009). In the loose quasi-dynamic strategy (Figure 3), the BES transfers data to the CFD which in turn runs the former time step and returns its output to the BES. In the cross quasi-dynamic strategy (Figure 4), the BES and the CFD run simultaneously and exchange data at the end of each time step. The received data are used for the next time step.

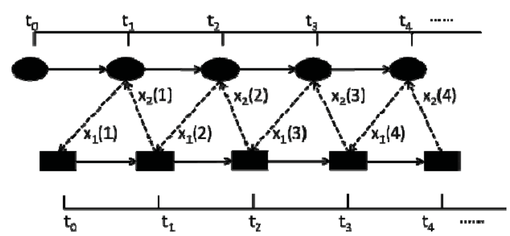

Figure 3 Loose quasi-dynamic synchronization

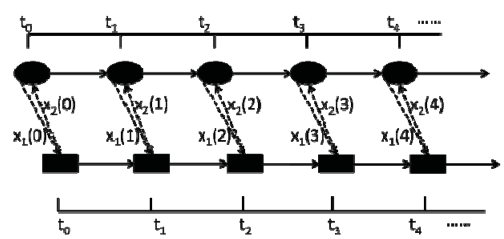

Figure 4 Cross quasi-dynamic synchronization

Fully dynamic synchronization strategy (Zhai, Chen et al. 2002) is also called onion coupling (Trcka and Hensen 2006) or strong coupling (Trčka, Hensen et al. 2009). It requires two programs to conduct multiple data exchanges within every time-step until convergent solutions are achieved for both simulations (Figure 5). Compared to the quasi-dynamic synchronization, the fully dynamic synchronization is more accurate but significantly slower, which can be a severe limitation for many applications (Zhai and Chen 2003).

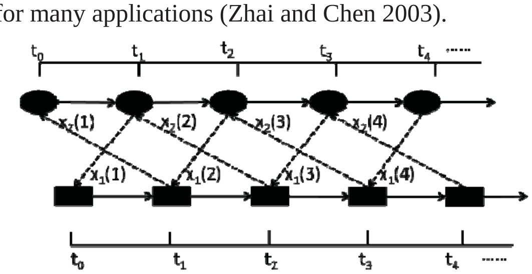

Figure 5 Fully dynamic synchronization

3.3. Bin Synchronization Strategy

The bin synchronization strategy (Zhai and Chen 2005) is also called virtual dynamic strategy (Zhai, Chen et al. 2002). As shown in Figure 6, it integrates indirectly the BES with the CFD through an intermediary, such as a database (Zhai, Chen et al. 2002), a neural network (Rong, Da et al. 2011), or a fitted formula (Pan, Li et al. 2010; Hiyama and Kato 2011; Zhang, Hiyama et al. 2013). The intermediary is established based on pre-computed CFD simulations in typical scenarios For some typical scenarios the CFD will iterate with the BES, and the results will be transferred to a database, with which the BES then is coupled to simulate the building energy consumption. With no CFD run during the coupling, the bin synchronization strategy is computationally faster than the dynamic synchronization. However, the accuracy of the bin synchronization strategy may significantly drop if the flow conditions are outside the range of pre-computed CFD simulations (Zhai, Chen et al. 2002).

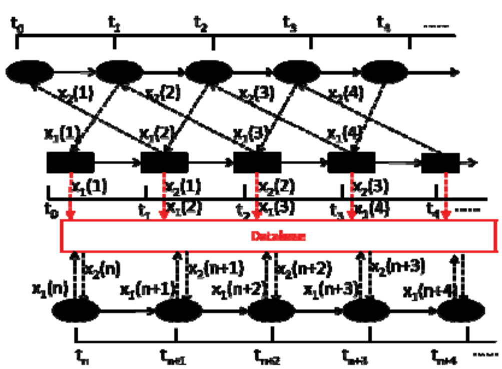

Figure 6 Bin synchronization

4. SOFTWARE ARCHITECTURE

The software architecture focuses on how to implement the software coupling. In general there are two methods: internal coupling and external coupling.

4.1. Internal Coupling

The internal coupling approach adds physical models of BES, such as the envelope heat transfer model and the envelope radiation model, into the CFD. As a result, the new integrated CFD program solves all the governing equations simultaneously until it reaches a converged solution. There are two major limitations in the internal coupling approach (Djunaedy, Hensen et al. 2003):

Solving heat transfer through the envelope by the CFD is computationally demanding due to the different time scales in the physical process. The heat transfer through the envelope may take hours while the airflow changes happen in a few seconds.

It is difficult to obtain a converged result due to the difference in the stiffness of fluid and solid equations (Chen, Peng et al. 1995).

4.2. External Coupling

Two methods for external coupling are reported in the literature. One is called discontinuity mechanism, which is define as “exchanging data between two programs sequentially, where a model preprocessor transforms the output of one program into the input for a slave program after the master program completes its simulation” (Djunaedy, Hensen et al. 2005). The other is a continuity mechanism, by which two programs are called separately and run in parallel (Trcka and Hensen 2006). The external coupling has at least four advantages as to the internal coupling (Djunaedy, Hensen et al. 2005):

it is much faster than the internal coupling (Djunaedy, Hensen et al. 2004). Since it is not necessary to iterate two programs to converge at each time step, the run time of coupled simulation can be dramatically reduced.

there is no computational stiffness as the two programs run separately.

it can take the advantage of the state-of-art technology in either program as there is no need to rewrite the code.

the program can be optimized individually in order to solve some specific problems.

To implement data exchange by external coupling, researchers have developed different methods, such as using a self-developed interface for direct coupling, a data exchange platform, and a standard interface. The main function of the self-developed code is to transform the output from one program into a recognizable pattern for the other program (Liping and Hien 2007; Fan and Ito 2012).

The data exchange platform allows programs to exchange data with other programs after connected to the platform. (Trčka, Hensen et al. 2009) presented several data exchange platforms for co-simulation of building performance. A popular approach, the Building Controls Virtual Test Bed (BCVTB) (Wetter 2010) is one of the more advanced methods for building performance simulation. However, it does not provide any links to commercial CFD software. It is necessary to develop a code to bridge the CFD and BCVTB, such as FLOW+ which is used to connect the CFD program FLUENT to the BCVTB (Zhang, Lam et al. 2012).

Two standard interfaces are developed for coupling CFD and the BES: Functional Mockup Interface (Blochwitz, Otter et al. 2011) and building product model based on International Standard Organization standard (Lydon, Keane et al. 2005).

5. USE CASES

The coupled simulation of BES and CFD can be used for various applications. It was used to evaluate the performance of the advanced indoor ventilation method, such as personalized ventilation, displacement ventilation, and natural ventilation (Zhang, Lam et al. 2012). It was adopted for the design of the advanced air-conditioning methods, such as underfloor heating with a top return (Fan and Ito 2012) and local thermal environment control (Steeman 2009). Moreover, it was applied for the study of thermal performance of double-skin facades (Zeng, Li et al. 2012), double-skin wooden roof (Villi, Pasut et al. 2009), and membrane (Devulder, Wilson et al. 2007) where flow within and around complex geometry is involved. Furthermore, (Goldsworthy 2012) used it to investigate mechanical ventilation for smoke control and (Bouyer, Inard et al. 2011) applied it to improve the microclimate condition around the building for BES.

6. CONCLUSION

By coupling the CFD and BES, we can obtain more complementary and accurate information about the indoor environment and building energy performance than single program alone. The exchange data can be synchronized by mainly three ways: static coupling, dynamic coupling and bin coupling. These strategies vary in time cost, simulation speed and accuracy. To implement the data exchange between the two programs, internal and external coupling are feasible. External coupling, which exchanges data externally out of programs by a self-developed code, a standard interface, or a data exchange platform, is preferred for it is faster and easily converged performance.

The coupled simulation can achieve satisfactory simulation for some applications. However, the coupled simulation still needs to be improved for the design and performance evaluation of indoor environment control. For instance, model-based HVAC control to prevent the spread of smoke when there is a fire emergency in buildings. This requires a fast computing speed for indoor environment simulation and dynamic simulation capability for HVAC control. The fast fluid dynamics (Zuo and Chen 2009) model is about 50 times faster than the CFD and can provide sufficient results for the smoke control. The Modelica models are dynamic and well-suitable for HVAC control (Wetter, Zuo et al. 2013). Coupling the FFD and Modelica may enable a fast and dynamic simulation for the indoor environment control.

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REFERENCE

1.Ascione, F., Bellia, L. and Capozzoli, A. (2012) "A coupled numerical approach on museum air conditioning: Energy and fluid-dynamic analysis", Applied Energy.

2.Blochwitz, T., Otter, M., Arnold, M., Bausch, C., Clauß, C., Elmqvist, H., Junghanns, A., Mauss, J., Monteiro, M. and Neidhold, T. (2011) "The functional mockup interface for tool independent exchange of simulation models". In: Proceedings of Modelica'2011 Conference, March, pp. 20-22.

3.Bouyer, J., Inard, C. and Musy, M. (2011) "Microclimatic coupling as a solution to improve building energy simulation in an urban context", Energy and Buildings, 43, 1549-1559.

4.Chen, Q., Peng, X. and Van Paassen, A. (1995) "Prediction of room thermal response by CFD technique with conjugate heat transfer and radiation models", ASHRAE TRANS, 101, 50-60.

5.Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. (2008) "Contrasting the capabilities of building energy performance simulation programs", Building and environment, 43, 661-673.

6.Devulder, T., Wilson, R. and Chilton, J. (2007) "The thermal behaviour of buildings incorporating single skin tensile membrane structures", International Journal of Low-Carbon Technologies, 2, 195-213.

7.Djunaedy, E., Hensen, J. and Loomans, M. (2003) "Toward external coupling of building energy and airflow modeling programs", ASHRAE Transactions, 109, 771-787.

8.Djunaedy, E., Hensen, J. and Loomans, M. (2004) "Comparing internal and external run-time coupling of CFD and building energy simulation software". In: Proceedings of Proc. 9th Int. Conf. on Air Distribution in Rooms-ROOMVENT, pp. 5-8.

9.Djunaedy, E., Hensen, J. and Loomans, M. (2005) "External coupling between CFD and energy simulation: implementation and validation", ASHRAE Transactions, 111, 612-624.

10.Fan, Y.Q. and Ito, K. (2012) "Energy consumption analysis intended for real office space with energy recovery ventilator by integrating BES and CFD approaches", Building and environment, 52, 57-67.

11.Goldsworthy, M. (2012) "Dynamic coupling of the transient system simulation and fire dynamics simulation programs", Journal of Building Performance Simulation, 5, 105-114.

12.Hiyama, K. and Kato, S. (2011) "Integration of three-dimensional CFD results into energy simulations utilizing an Advection–Diffusion Response Factor", Energy and Buildings, 43, 2752-2759.

13.Liping, W. and Hien, W.N. (2007) "The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore", Building and environment, 42, 4006-4015.

14.Lomas, K.J. (1996) "The UK applicability study: an evaluation of thermal simulation programs for passive solar house design", Building and environment, 31, 197-206.

15.Lydon, G., Keane, M. and Ingham, D. (2005) "Implementation of an interface between a CFD energy analysis and an IFC building product model". In: Proceedings of Information Visualisation, 2005. Proceedings. Ninth International Conference on, pp. 277-286.

16.Ohba, M. and Lun, I. (2010) "Overview of natural cross-ventilation studies and the latest simulation design tools used in building ventilation-related research", Advances in Building Energy Research, 4, 127-166.

17.Pan, Y., Li, Y., Huang, Z. and Wu, G. (2010) "Study on simulation methods of atrium building cooling load in hot and humid regions", Energy and Buildings, 42, 1654-1660.

18.Rong, Q., Da, Y., Xin, Z. and Yi, J. (2011) "Research on a dynamic simulation method of atrium thermal environment based on neural network", Building and environment.

19.Steeman, H.-J. (2009) "Modelling local hygrothermal interaction between airflow and porous materials for building applications".

20.Trcka, M. and Hensen, J. (2006) "Model and tool requirements for co-simulation of building performance". In: Proceedings of Proceedings of the 15th IASTED Int. Conf. on Applied Simulation and Modelling, pp. 26-28.

21.Trčka, M., Hensen, J.L. and Wetter, M. (2009) "Co-simulation of innovative integrated HVAC systems in buildings", Journal of Building Performance Simulation, 2, 209-230.

22.Trcka, M., Wetter, M. and Hensen, J. (2007) "Comparison of co-simulation approaches for building and HVAC/R system simulation", Proceedings of the Building Simulation 2007, 1418-1425.

23.Villi, G., Pasut, W. and Carli, M.D. (2009) "CFD modelling and thermal performance analysis of a wooden ventilated roof structure". In: Proceedings of Building Simulation, Vol. 2, pp. 215-228.

24.Wang, L. and Chen, Q. (2008a) "Applications of a Coupled Multizone-CFD Model to Calculate Airflow and Contaminant Dispersion in Built Environments for Emergency Management", HVAC&R Research, 14, 925-939.

25.Wang, L. and Wong, N.H. (2008b) "Coupled simulations for naturally ventilated residential buildings", Automation in Construction, 17, 386-398.

26.Wetter, M. (2010) "Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed", Journal of Building Performance Simulation, 4, 185-203.

27.Wetter, M., Zuo, W., Nouidui, T.S. and Pang, X. (2013) "Modelica Buildings library", Journal of Building Performance Simulation.

28.Zeng, Z., Li, X., Li, C. and Zhu, Y. (2012) "Modeling ventilation in naturally ventilated double-skin façade with a venetian blind", Building and environment.

29.Zhai, Z., Chen, Q., Haves, P. and Klems, J.H. (2002) "On approaches to couple energy simulation and computational fluid dynamics programs", Building and environment, 37, 857-864.

30.Zhai, Z. and Chen, Q.Y. (2003) "Solution characters of iterative coupling between energy simulation and CFD programs", Energy and Buildings, 35, 493-505.

31.Zhai, Z.J. and Chen, Q.Y. (2005) "Performance of coupled building energy and CFD simulations", Energy and Buildings, 37, 333-344.

32.Zhang, R., Lam, K.P., Yao, S.-C. and Zhang, Y. (2012a) Annual coupled EnergyPlus and computational fluid dynamics simulation of natural ventilation, SIMBuild.

33.Zhang, R., Lam, K.P., Yao, S.-C. and Zhang, Y. (2012b) "Coupled EnergyPlus and Computational Fluid Dynamics Natural Ventilation Simulation". In: Proceedings of Proceedings of 5th National SimBuild Conference.

34.Zhang, W., Hiyama, K., Kato, S. and Ishida, Y. (2013) "Building energy simulation considering spatial temperature distribution for nonuniform indoor environment", Building and environment.

35.Zuo, W. and Chen, Q. (2009) "Real-time or faster-than-real-time simulation of airflow in buildings", Indoor Air, 19, 33-44.