ON INTEGRATION OF CFD IN BUILDING DESIGN

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ABSTRACT

CFD simulation is a powerful tool that can help to improve the building design process. This presentation argues that the best way to integrate the CFD into the building design is by coupling it to energy simulation, and in particular by using external run-time coupling for that purpose. A guideline to approach the coupled simulation is presented, along with an implementation of the external coupling method.

INTRODUCTION

CFD simulation has become an influential tool in the building industry, especially with its capability to visualise airflow in and around buildings. However, since its application in the building-related problems is still in its infancy, its place in the building design is not yet recognized. The CFD role in the building design can be categorized into at least three levels (these levels also apply to all simulation tools in general):

1. To justify the final design
   In this level, the role of CFD is very limited. The design process is almost complete, and CFD is needed only as a confirmation for the already finished design.

2. To justify the selection of design options
   In this level, CFD enjoys a greater role. CFD is used not in the very end of the design process, but sometime earlier. However, its role is still limited to a confirmation tool to select the already-finished designs.

3. To collaborate with other design tools in the cycle of refinements towards the final design.
   This level is the ideal role of CFD. CFD is used not only as a justification or confirmation tool, but actually involved in shaping and molding the design. There is a feedback from the CFD result to the drawing board where the design will be refined.

So far, CFD and other building simulation tools has not enjoyed its honorable status in the design process. Only limited numbers of design practitioners have committed to the extensive use of simulation tools. (For further discussion on this topic, see McElroy and Clarke 1997 and Morbitzer et al. 2001).

The typical use of CFD is generally characterized by the following practices:

1. Tool-led, i.e. CFD is used not because it is the most appropriate tool to solve a certain problem, but simply because CFD is available and can give impressive visual images.

2. Isolated worst case scenario, for which the simulation is performed. The dynamic conditions of the building is usually ignored.

3. Unjustified boundary conditions that is used for the CFD simulation.

This paper argues that the above practices should be avoided to have the optimal benefits from CFD simulations. Firstly, the use of any simulation tool (including CFD) should be problem-led, i.e. the problem at hand is best solved by CFD and not with other tools. Secondly, CFD should be seen as part of an array of simulation tools that can interact with each other. Using this view, CFD simulations will not be an isolated worst case scenario, but a selected worst case scenario among other possible scenarios. Moreover, different simulation tools can share their result to be used by the others as a boundary condition, for which case the boundary condition will be more accurate.
This paper will focus the discussion around two topics: (1) the guideline to select an appropriate (airflow) simulation tool for a certain problem and (2) the external run-time coupling between CFD and energy simulation. These two topics are the presented as the approach towards the integration of CFD into building design.

GUIDELINE FOR SELECTING APPROPRIATE TOOL FOR AIRFLOW SIMULATION

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) analyze the capability and applicability of these approaches in the context of 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 (more complex) approach does not necessarily provide answers to all the design questions that may be answered by a lower resolution (less complex) approach.

These are important findings in the middle of the abundance of simulation tools. When the various tools become available, it should be realized that high resolution (and more complex) approach requires 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. Often, the sophistication of the approach would not fail to impress a client. However, the cost of such sophistication should always be justified. Failing to do so will only make the client hesitate to use the method in the future. The positive growth in the widespread use of simulation in building design could be affected by this.

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 they called "early assessment design strategies" (Figure 1a). From 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 a new innovative design altogether. Based on this initial assessment, and with the proposed HVAC strategy, several decision points in Figure 1 would help the engineer to decide which level of complexity should be used for simulation.

Our proposed guideline is developed based on the findings of the previous research described above. Early assessment design strategies as proposed by Slater and Cartmell (2003) can be used for initial assessment. However, we indentified the need to go further because of the following reasons:

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

Figure 1b shows the proposed Coupling Procedure Decision Methodology (CPDM). It is initially developed as part of a research in coupled simulation between CFD and BES (Djunaedy et. al. 2003). The fact that coupled CFD and BES simulation is computationally expensive requires that the simulation is justified by a sound rationale. CPDM was proposed to identify the need for coupled simulation.

The main ideas behind the CPDM are:

1. a simulation should be consistent with its objective, i.e. the designer should not be tool-led,
2. there should be a problem-led rationale to progress from one level of resolution and complexity to the next,
3. Simulation 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 1b) 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 CFD simulation. Each of the resolution layers is separated by one or more decision layers. The horizontal axis shows the different level of complexity of building simulation.

(a)
Figure 1 (a) Early assessment design strategies (Slater and Cartmell, 2003)
(b) Coupling Procedure Decision Methodology

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

- If energy consumption is needed, then BES would be sufficient.
- If temperature gradient is needed, then 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:

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

Sensitivity analysis

Sensitivity analysis is the systematic 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 field of engineering as a what-if analysis, and one example of the use of this method in building simulation is Lomas and Eppel (1992).
For the CPDM, the sensitivity analysis will be used for decision making tool. From previous studies (e.g. Hensen 1991, Negrao 1995, and Beausoleil-Morrison 2001), there are two main inputs that should be tested for sensitivity analysis for the decision to progress to higher resolution level:

- Airflow parameters assumption, especially the infiltration rate, for the decision to use AFN-coupled simulation.
- Convection coefficient, for the decision to use CFD.

Figure 2 shows two scenarios on how to use the CPDM. Each of the performance indicators would have a “target value” that can be found from building codes, standards, or guidelines, or even from “good-practices” experience. The target value can be a maximum value, minimum value, or a range of acceptable values. The result of the SA would be presented as a bar chart with three output conditions of the performance indicators, each of which corresponds to the minimum value, maximum value, and base condition value of input.

In Figure 2(a), the output value could be more than the maximum target value, based on the result of BES-only simulation, and the SAa result indicated that the AFN-coupled in necessary. However, in the AFN-level, the SAhc result indicated that all predicted values are below the maximum target value, thus no subsequent CFD calculation is required.

![Figure 2 Different scenarios in sensitivity analysis in the CPDM](image)

In Figure 2(b), the output value could be less than the minimum target value, based on the result of BES-only simulation, and the SAa result indicated that the AFN-coupled in necessary. In the AFN-level, the SAhc result indicated that there is a possibility that the output value is below the minimum target value, thus CFD calculation is required.

The above guideline was tested on a case study, which has been reported in earlier publication (Djunaedy et. al. 2003). The case study concluded that the guideline can help the selection of simulation tool to solve a certain problem.

EXTERNAL COUPLING BETWEEN CFD AND ENERGY SIMULATION

The coupling of building energy simulation (BES) and computational fluid dynamics (CFD) simulation has been discussed in various publications in recent years, e.g. Negrao (1998), Srebric et al. (2000), Beausoleil-Morrison (2000), Zhai et al. (2002). The two simulation programs, as in any simulation program, 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 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 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. For example, BES can provide internal surface
temperatures of the walls to CFD, while CFD can provide more accurate CHTC for BES. The benefits of the coupled simulation has been discussed in the publications mentioned.

Djunaedy et. al (2003) discussed different approaches to couple the two programs. Here, internal coupling is regarded the “traditional” way of coupling, i.e. expanding the capabilities of existing software by adding new modules into an existing program. Internal coupling can also be seen as subroutinazation. External coupling on the other hand makes use of existing packages in different domain (for example the thermal domain for energy simulation and the flow domain for CFD), and provides a mechanism for these programs to communicate.

External coupling could mean exchanging data between two programs sequentially, where a model-preprocessor transforms the output of one program into an input for another program after the first program completed the simulation. For this study, “external coupling” is defined as run-time communication between two separate program where at least one of the program continues to run while exchanging information with the other program.

There are at least two reasons to use external coupling. Firstly, each domain application has evolved separately over the years and is well proven. Rewriting the code (to be included as part of a package in another domain) could be seen as a set back from these independent advances in separate domains. Therefore, Further efforts should better be concentrated at making these different domain applications to communicate with each other.

Secondly, external coupling can immediately benefit from independent developments in each domain. The separate domain applications can expand and develop in their respective directions, and the external coupling mechanism can make this development available without having to (heavily) update the source code.

**Different implementation of coupling strategies**

The energy calculation of the BES is sensitive to the value of the convective heat transfer coefficient (CHTC) and the reference temperature used in the above equation. Without CFD, the best BES can do is to adaptively use empirical correlations during the simulation, and use the air-point temperature as reference temperature. The main disadvantage is that it cannot include the effect of temperature stratification around the wall, and also the difference in flow characteristics between surfaces in the same room. CFD is introduced to overcome those problems. However, the parameters in the equation must be resolved iteratively, by exchanging the parameters between the two programs until the values are converged.

Negrao (1995) describes two handshaking mechanisms between the BES and CFD: the surface coupling and integrated coupling. In integrated coupling, CFD interacts directly with the thermal matrix solver and resolves the exchanged parameters until the values are converged. CFD is used to solve the zone air-point temperature and the internal surface convection, while the BES provides the CFD with the internal surface temperatures. Both iteratively exchange the data until convergence before moving to the next time step.

In surface coupling, on the other hand, the two programs work independently and exchange information at the internal surfaces. The CFD uses the boundary conditions (wall temperature) from the previous time step, calculates the convection heat transfer coefficient (CHTC) and sends this back to the BES. The BES will then use this information to form the matrix for the zone heat balance equations and solves the matrix for the current time step. The simulation continues with CFD simulations always use the data from the previous time step.

Beausollel-Morrison (2000) argued that surface coupling brings many advantages over the integrated approach. For external coupling, the most important feature is that the surface conflation provides more flexibility in defining the coupling mechanism. With regard to accuracy, obviously integrated conflation is more accurate because it resolves the exchanged data in many iterations until converged to a certain value. However, the accuracy will be the same if the time step is sufficiently small.

Zhai and Chen (2001) found that in the iteration between CFD and BES, the solution does exist and is unique. Zhai and Chen also reported that normally convergence can be reached after 4 – 10 iterations. If we take one hour as the standard time step in most BES, we can conclude that a 6 to 15 minutes time step is small enough for surface conflation to get the same accuracy as the integrated conflation.

Furthermore, the CFD-predicted value of CHTC (CHTC_{CFD}) can always be rejected in surface conflation. This cannot be done in integrated conflation without interrupting the iteration process. This checking mechanism of the CHTC_{CFD} value before passing it back to BES is one of the quality assurance measures that should be used when using surface conflation.
Figure 3 Internal coupling mechanism in ESP-r

Figure 3 gives an overview of the current status of surface coupling (Beausoleil-Morrison, 2000) and ESRU 2000). In summary, for 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. If yes, it will invoke the coupling controller to derive the CHTC from a CFD simulation. The coupling mechanism consists of a pre-CFD treatment, the CFD simulation and a post-CFD treatment.

The calculated CHTC_{CFD} is then compared with a CHTC value that is determined from empirical correlations applicable to the flow field under investigation. 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 empirical correlation.

A case study was done to validate the implementation of external coupling. The test cell under investigation is located in Bedfordshire, UK. Figure 4 shows the site layout and the situated test cells. A detailed description of the site and the test room can be found in Lomas et al (1994).

Figure 4 Test cell site (Photo from Lomas et al 1994) and the model for simulation

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 used in this study.

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 uses an ideal controller to inject the heat 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 detailed description and result of the case study was reported in (Djunaedy 2004). This paper will summarize one result of the case study.

![Diagram of CHTC of window](image)

**Figure 5  CHTC of window (26-Oct)**

Figure 5 shows the CHTC for the window. Most of the time, the internal coupling result shows exactly the same values with the empirical values. 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/m²K) for this type of flow. The external coupling simulation, on the other hand shows, consistently similar values for the CHTC (around 10 – 14 W/m²K), which is higher than the values calculated by empirical correlations.

External coupling also shows a better solver performance, i.e. capability of handling finer mesh, more accurate, and more powerful (24 mins of simulation compared to 10hrs for internal coupling).

**CONCLUSIONS**

Both the guideline and external run-time coupling are approaches that can be used to integrate CFD into the building design. The guideline will ensure that the simulation always use the appropriate tool. The external coupling will (1) increase the accuracy of the boundary conditions by using the result of other simulations, and (2) provides the independent development of simulation tools.

**REFERENCES**


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