Dynamic simulation of cross-ventilated buildings with night-flush cooling in neighbourhood environment using integrated CFD-CFD-BES strategy

Ruijun Zhang\textsuperscript{1}, Parham A Mirzaei\textsuperscript{1,*}, Benjamin M Jones\textsuperscript{1}

\textsuperscript{1} Department of Architecture and Built Environment, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
\textsuperscript{*} parham.mirzei_ahranjani@nottingham.ac.uk

Abstract. Night flush cooling is an effective passive strategy to condition spaces and provide larger capacity to store heat. A common technique to quantify the benefit from this cooling strategy is using building energy simulation (BES) modelling, which, however, is weak in capturing the airflow patterns and convective heat transfer under the complex urban contexts. Therefore, dynamic coupling techniques of BES to computational fluid dynamics (CFD) are often used to improve the simulation performance of the night flush cooling strategies.

Nonetheless, dynamic coupling techniques always encounter a high computational cost to achieve accurate CFD calculations for naturally ventilated scenarios, as high-resolution grids are required to be prepared. Therefore, a framework of integration of a fine-resolution CFD grid (CFD\textsubscript{f}), a coarse-resolution CFD grid (CFD\textsubscript{c}) and BES is proposed in this work to study night-flush cooling. In this framework, the CFD\textsubscript{f} domain performs as the off-line module that generates the boundary conditions for the CFD\textsubscript{c} domain at its openings before the start of the iterative calculations. CFD\textsubscript{c} and BES domains are then performing a fully dynamic external coupling to achieve a convergence for the energy simulation using the updated convective heat transfer coefficient (CHTC) profiles at the exterior surfaces. A case study is investigated for a simple urban morphology in Los Angeles on a typical hot day. The results highlight an improvement in representation of the neighbourhood effect in energy calculations obtained in a feasible calculation run-time.

1. Introduction
Natural ventilation is one of the most common passive strategies to improve indoor comfort and conserve building energy [1]. As an effective design of natural ventilation, night-purge cooling is accomplished with keeping ventilation openings closed during the day while opening them at night, so that the warm indoor air is flushed and cooled to get the space prepared as the sink for the next day. This technique is mainly useful in commercial buildings where highly insulated walls with high internal heat gains released from people, lighting and other equipment result in an intense cooling demand. Assessments of building performance and strategy efficiency widely rely on building energy simulation (BES) modelling tools such as Revit, EnergyPlus, TRNSYS, etc.

These BES tools use empirical functions for the surface convection at the building surfaces; however, the complex microclimate around buildings is normally simplified or ignored, especially in dense urban area. The misestimated energy demand is found as 20-40\% due to the use of simplified outdoor air models [2, 3]. As a solution, coupling BES tools with computational fluid dynamics (CFD) technique, which is powerful in the external/internal airflow modelling, is developed in several studies [4-8]. At present, the coupling method is mainly used for calculation of interior surfaces’ convective heat transfer coefficient (CHTC) while its application on exterior surfaces is still limited. The coupling is also barely conducted for the case of hybrid indoor-outdoor natural ventilation. Existing models for CFD simulations of naturally ventilated scenarios can be categorized as three types, including hybrid
indoor-outdoor, indoor-only, and regionally decomposing. The indoor-only method is over-simplified in representing outdoor environments, as it is difficult to define the boundary conditions at the openings. With the hybrid method, dense grids are required to capture smaller-scale indoor space features; however, doing so will greatly increase the size of computational model, as the domain scale for neighborhood modelling is usually large [9]. In such cases, the challenge is to reduce the computational cost of dynamic modelling without compromising quality of the results. Therefore, the regionally decomposing type becomes a competitive choice, especially when CFD is involved in an iterative calculation.

This study aims to develop a practical general framework to benefit from a fine-resolution grid CFD (CFDf), a coarse-resolution grid CFD (CFDc) and couple them with a BES model to improve the energy modelling of naturally ventilated buildings. The performance of the developed framework is shown using a case study of a commercial building during a typical hot day located in Los Angeles.

2. Method
The whole coupling process is divided into two stages, including off-line preliminary simulation and online dynamic simulation (see figure 1). CFDf and BES participate in the off-line preliminary stage so that the CFDf’s results are fixed and not being updated during the iterative calculation in the dynamic stage whilst BES’s results at this stage are treated as the initial guess for the iterative process. Simulation of building energy uses a fully dynamic approach to ensure that the convergence between CFDc and BES is achieved at each time step. For this study, both domains should achieve a consistent convective heat flux \( q_c \) within an accepted margin (less than \( 10^{-2} \) K) at the outdoor surfaces at every time-step before moving to the next one.

![Diagram of coupling CFD-CFD-BES](image)

**Figure 1.** Framework of coupling CFD-CFD-BES for natural ventilated buildings’ exterior surfaces.

The difference between CFDf and CFDc can be explained as the CFDf model contains both indoor and outdoor domains with a high-resolution grid whilst CFDc only contains the outdoor domain with a coarse grid. As the indoor part is removed, inflow and outflow boundaries are required for the buildings in the
CFDc domain to represent the ventilated surfaces. The setup information of these boundaries is obtained from the results of the CFDf simulation.

Figure 1 shows schematic of the proposed coupling CFD-CFD-BES process for energy assessment of the naturally ventilated buildings as shown in figure 2. A bespoke code is developed to establish the coupling process while it works as a transfer station between three domains, weather data, domain geometry and other operating conditions. A pre-simulation is performed for a short period (can be a few hours) earlier than the test day to include the time lag effect in the thermal calculations as well as throughout the test day. For the CFDf domain, the run period is the purging time from the night to the early morning; in this study, from 1am-6am and 7pm-12am when the offices are relatively empty. The flow patterns, including the velocity components and turbulence data at the opened (ventilated) surfaces, are recorded for a later coupling with the CFDc domain. CFDf is placed in an off-line block because its output will not be changed or updated in the subsequent dynamic simulations. BES uses an embedded algorithm to calculate the CHTC in the preliminary stage to provide initial values for the subsequent iterative process. Then, its convection control function is switched to ‘user input’ mode to receive more accurate results provided by CFDc. The boundary conditions of CFDc are determined by climatic conditions from weather data, by ventilated (opening) conditions from CFDf and by other exterior surface thermal conditions from BES. In this study, building surface temperature ($T_s$) and CHTC are adopted as the exchange media between CFDc and BES. In more details, BES provides $T_s$ to CFDc and CFDc returns the CHTC to the bespoke code to update the CHTC schedules in BES.

The principle of the iterative process is to achieve a unified convective heat flux ($q_c^{\ast}$) in both of the CFD and BES programs. A virtual CHTC, $h^{\ast}$, needs to be introduced to work as an adapter, helping EnergyPlus (its convection calculation is based on a fixed air temperature, $T_{a,z}$ at a certain height in a given weather data) to receive the same amount of convective heat gain generated in the CFDc domain, which uses the actual temperature of the adjacent flow $T_{a,s}$. Therefore, in the iterative process, it can be calculated via:

$$h_{i+1}^{\ast} = \frac{q_{c_{\text{CFD}}}}{(T_s-T_{a,z})},$$

where $i$ specifies the current iteration index.

Figure 2. Plot of a) arrangement of nine cuboid buildings and b) ventilated surfaces.

A case study of a city neighbourhood with a simple morphology consisting of nine cuboid buildings (10m × 10m × 10m) in 3×3 array with each street canyon of unity aspect ratio is provided in this study as seen in figure 2. Each building is divided into three layers with windows W1 on the top, which has two layers opened for night flushing. The CFDf model was created using the validated configurations by [10] containing approximately 7.5 million cells, and it was run by CFX 19.1, whilst the CFDc model was referred to a validated model by [7] with only 130k cells and was run by FLUENT 19.1. The BES model is developed from a commercial benchmark case of U.S. Department of Energy (DOE) [11]. The
simulation was executed for a typical hot day in Los Angeles U.S. from 1am to 7am, including 6-hour of purging period in addition to the first hour after the end of the night-purge period.

3. Results

3.1. Benefits of CFDf – CFDc

Velocity boundaries are employed in CFDc in an attempt to reproduce the same or similar features of ventilating surfaces as those captured in CFDf. To do so, the velocity vectors were determined using components in three dimensions obtained from CFDf. Table 1 provides the root mean square error (RMSE) of the representing local flow parameters, including pressure coefficient \( C_p \), flow velocity \( U \), pressure \( p \) and mass flow rate \( m \) at all the ventilated surfaces by CFDc compared to those obtained by CFDf. As seen from the table, the accuracy in terms of pressure coefficient and pressure is found to be lower than other two parameters, but still within an acceptable margin. The selected velocity boundaries present a highly accurate result in terms of velocity and mass flow rate. There are 58 test lines (34 vertical with 24 horizontal lines) in the street canyons to monitor the capability of CFDc in capturing both vertical and horizontal flow patterns. Figure 3 shows RMSE of the normalized local velocity of these lines against the approaching wind speed.

| Flow parameter | RMSE |
|----------------|------|
| \( C_p \)     | 0.658 |
| \( U \)       | 0.104 |
| \( p \)       | 0.655 |
| \( m \)       | 0.000 |

Figure 3. RMSE of normalised U in different monitoring regions.

Although the accuracy is compromised when CFDc is used instead of CFDf, the benefits of this operation in terms of time and computational cost are considerable. In the same scenario, the simulation of CFDc only took 1/28 of the time required for the CFDf simulation. This value is even smaller when the energy equation is taken into the account.

3.2. Results comparison of BES-only and coupling methods

The CHTC convergence between CFDc and BES is guaranteed with a criterion of 0.01. However, if necessary, the criterion would be broadened to maintain efficiency faster convergence. For example, in this case study, if convergence was still not achieved within the limit of 10 iterations, then, the criterion needed to be changed to 0.1. Figure 4 shows the iteration numbers performed for each time-step to obtain reliable results.

Figure 5 shows deviation of the zonal temperatures for the central building (see B5 in figure 2) derived by the proposed coupling and BES-only (which uses a default CHTC algorithm of DOE-2) methods along with their reported run-time period. All positive values indicates that the calculation by DOE-2 underestimates the zone temperature. From 1am to 6am, the two top floors are naturally ventilated while the ground floor (GF) is almost sealed. Since the temperature of the naturally ventilated area is more dependent on the outdoor air temperature, the temperature difference on the GF should be greater than the other two. However, during the purging time, the temperature difference on the second floor (SF) is found to be the largest one. This phenomenon shows that the coupling process to update the CHTC has a great influence on the roof surface that it can even make the ration of convection to heat balance exceeding the one by ventilation. This finding is confirmed by that a highest deviation, occurring at the second floor (SF) within the 7th hour of the day when the difference on the GF and first floor (FF) is negligible (see figure 5).
Figure 4. Iteration numbers to achieve convergence.

Figure 5. Difference of temperature of three zones in Building 5 computed by coupling method and BES-only.

Figure 6. Standard deviation of the surface CHTC by BES-only and coupling methods.

EnergyPlus, and many other BES tools over-simplify the effect of wind angles only by distinguishing walls into two options, including windward or leeward. Their embedded CHTC algorithms ignore the difference related to the location of the buildings. CFD simulations can significantly improve the airflow modelling, and thereby represent sheltered scenarios better. Figure 6 clearly shows the standard deviation of the CHTC at four exterior surfaces at different altitude in the city area. The standard deviations obtained by BES is very small, and the highest value is less than 0.03, which means neglecting of the neighbourhood effect. In contrast, after applying the coupling method, the neighbourhood effect is fully reflected and the standard deviation rises sharply, especially at the roof surfaces. During the night-purge period, the standard deviation of the roof CHTC by BES-only is approximately 2.1E-04 comparing to that 1.7E+00 by the coupling method. Moreover, in the 7th hour of the day, it is found as 7.1E-06 by BES-only comparing to 2.1E+00 by the coupling method.
4. Conclusion
A framework of a fully dynamic coupling of CFDf, CFDc and BES is developed to model naturally ventilated spaces with enhanced exterior convection predictions in addition to an improved run-time efficiency. The concept of the coupling CFDf and CFDc is found to be feasible, especially in replication of the velocity filed and mass flow rate. Advantage of replacing CFDf with CFDc model for each simulation in conservation of the run time is considerable; it only takes less than 1/28 of the initial time by CFDf. The coupling method is effective in improving the expression of neighbourhood effect while the strongest reflection occurs on the roof surfaces. Standard deviation of all corresponding surfaces temperature is 1.7E+00 by the coupling method compared to 2.1E-04 by BES-only method during the purging hours. The developed framework is thereby proposed as feasible and competitive method to be applied to model the energy of buildings with natural ventilation in sheltered urban area.

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