An Alternative Approach to the Simulation of Wind Effects on the Thermal Performance of Buildings

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Abstract: The new method described in this paper incorporates the wind effect surrounding the buildings into the external air temperature by the use of an equivalent temperature (called here $T_{natural}$) which produces the same rate of convection heat loss like that with the wind effects included. The internal air temperature of the building can be then calculated using this new external air temperature $T_{natural}$. Simulations using this approach were compared with the real data from four existing housing test modules incorporating a range of walling systems, resulted in an accurate, representative analysis as well as a significantly reducing simulation time.

Keywords: Building Thermal Performance; CFD Building Simulation; Wind Effect.

1 Introduction

Most building thermal assessment programs produce differences between projected theoretical energy loads (by energy assessment modules) and the actual energy consumption [1]. One of the leading programs used in building design is Autodesk Computational Fluid Dynamics (CFD) analysis. CFD analysis is capable of simulating the internal air temperature of buildings over long time periods, but lengthy computing times were required [2]. For this reason, energy simulation programs (BES) were combined with CFD analysis for building simulations, where the CFD simulation is used for short period simulations while the BES were used for long period simulations [3,4].

Generally, CFD analysis predicts turbulent flows through three approaches: direct numerical simulation (DNS); large-eddy simulation (LES); and Reynolds-averaged Navier-Stokes (RANS) equation simulation with turbulence models. The DNS method requires very small time steps, which makes the simulation extremely long [5]. When dynamic wind conditions were also considered, the computing time may become even more substantial and even with powerful computers, considerable computing time is still required [6].

2 Issues with Wind Simulations

There were many issues facing building thermal simulation such as; excessive computing time, time step size and divergence.

2.1 Time Step Size

In CFD analysis time step size depends on the time scale of the analysis and the type of analysis. For non-motion flow analyses, the time step size is a fraction of the mean flow
velocity, and should be at least a tenth of the time needed to traverse the length of the object being modeled. In many cases a much smaller time step size (1/20th) will be required to adequately resolve the flow [7]. For example in Autodesk CFD Simulation (2014), the time step size can be edited through the solver where the transient analyses can be terminated either when an exact time has been reached, or after a certain number of time steps (whichever comes first).

A useful guideline for the time step size is approximately 1/20th of the time required for a particle of fluid to traverse the length of the object. For example, for average wind speed \( V \) of 6m/s for a 6m long building (L):

\[
Total \ travel \ time = \frac{L}{V} = \frac{6m}{6m/s} = 1 \ second \tag{1}
\]

\[
Time \ step \ size = 1s \times \frac{1}{20} = 0.05s \tag{2}
\]

Using a time step size of 0.05 second (0.000835 minutes) will require a very long computing time, making it impractical for a building analysis simulating long-term behaviour (days and weeks) using a PC (as shown in the Table1).

| Computing time for one day | Computing time for one week | Computing time for 30 days | Computing time for a season (120 days) |
|----------------------------|----------------------------|---------------------------|---------------------------------------|
| 208 Days                   | 1247 Days                  | 5346 Days                 | 21385 Days                            |

Note: The simulation was carried out on Dell latitude e5440 with Intel ® Core ™ i5-4200 U CPU @ 2.3 GHz with 8GB RAM installed memory.

2.2 Divergence

The time step size for a typical solar heating analysis can be on the order of 100 seconds or more. Using a larger time step size (1 or 5 minutes) for a long-term analysis will lead to divergence. Divergence occurs when the outcome is no longer changed with additional iterations. This is because the iterative process is repeated until the change in the variable (outcome) from one iteration to the next one becomes insignificant (very small change). If the transient calculation is diverging, the time step size needs to be decreased requiring a longer computing time [8].

Most simulations were designed for shorter simulation (milliseconds, seconds, minutes and hours not for days, weeks or months), so applying the wind effect to the simulation requires very small time steps. This leads to excessive computing time or the simulation may reach convergence. For example, Autodesk Simulation CFD 2014 terminates the analysis when either 750 iterations have been completed or when the outcome reaches convergence; whichever comes first [9].

Smaller time steps for wind will make it impossible to simulate for long-term so a new method has been developed to speed up the simulation by merging the wind effect with the external air temperature surrounding the building.

3 Key Approaches Used in This Research

3.1 Housing Test Modules
Existing data collected from four, full-scale housing test modules was used to test the validity of the assumptions inherent in the new method which combined the effects of wind and external temperature. An on-going research programme on the thermal performance of housing has been underway for more than ten years in the Priority Research Centre for Energy at the University of Newcastle, Australia. The research has included the construction of four full-scale housing modules and monitoring them under a range of seasonal conditions to study their thermal performance – see Figure 1.

The housing test modules were part of a larger research program at the University of Newcastle on the thermal performance of housing. Each of the four full-scale housing modules was simulated using Autodesk CFD Simulation, with the simulation based on the external temperature data obtained from the test modules [10].

All the modules were constructed on the University of Newcastle, Callaghan Campus (Longitude 151.7E and latitude 32.9S). The modules were selected to signify typical forms of building in Australia. All modules were similar with a square floor plan of 6m x 6m as shown in Figure 1, spaced 7 m away from each other to reduce wind obstruction and avoid shading.

Each module had different walling systems, but shared the following characteristics:

- An entry door; heavily insulated door in the southern wall to eliminate any heat losses.
- A window in each northern wall from 6.38mm laminated clear glass in an aluminium frame.
- Roof covered with either concrete or clay roof tiles with sarking insulation, combined with a 10mm plasterboard ceiling with R3.5 glass wool batts insulation between rafters.
- A 100 mm thick concrete slab on ground concrete floor.

![Figure 1](image)

**Figure 1.** (a) Modules layout, (b) module dimensions which apply to all modules [10].

The only difference between the modules was the walling system:

- Cavity Brick Module (CB)
Walling system consisted of two 110mm brickwork skins with 10mm render covered the internal walls and 50mm cavity between the walls [10].

- Insulated Cavity Brick Module (InsCB)
  Walling system consisted of two of 110mm brickwork skins with the internal walls covered by 10mm internal render with the 50mm cavity insulated with R1 polystyrene insulation [10].

- Insulated Brick Veneer Module (InsBV)
  Walling system consisted of an external 110mm brickwork skin combined with an internal timber frame with low glare reflective foil and R1.5 glass wool batts, with the internal surface covered by 10mm plasterboard [10].

- Insulated Reverse Brick Veneer Module (InsRBV)
  Walling system consisted of an external wall of 2-3mm acrylic render on 7mm fibre cement sheets fixed to a timber stud frame insulated by R1.5 glass wool batts insulation. The internal wall consisted of a 110mm brick skin covered by 10mm internal render [10].

A Datataker DT600 was used to record data at 5 minute intervals through sensors installed in all modules to measure the external environment and internal air temperatures [10]. The interior of the modules was allowed to “free float” with the internal air temperature determined by the external weather conditions alone (with no mechanical heating or cooling). The internal air temperature was logged at a height of 1200mm inside the building, with all the modules being air tight and sealed during the study period [10].

3.2 Computational Fluid Dynamics (CFD)
In this paper Autodesk CFD 2014 is used as a simulation tool that mathematically analyses fluid flow and heat transfer using numerical approaches and algorithms [11]. The exact physical characteristics of each module were modelled using CFD analysis. Then a grid independence test was conducted to ensure that the CFD simulation was precise with the data obtained from the real modules.

3.3 Wind Data at the Site
The wind speed and direction changes with time. The wind speed and direction recorded at the site every 5 minutes for one week from 14/01/2010 to 21/01/2010 were shown in Figures 2 and 3.
Figure 2. Wind speed for one week recorded at the top of the building (4 metres from the ground).

Figure 3. Frequency of wind direction (percentage of time the wind is from each direction).

4 Methodology

There have been many previous attempts to simulate long-term wind effects by coupling two software programs for the short and long-term. However, this requires extensive computing time. In the current method one programme is used to simulate wind by incorporating wind effects in the equivalent external air temperature surrounding the building. This allows the use of use larger time steps (with faster computing times) without the simulation diverging [12].

To find the new external air temperature which causes the same rate of convection heat losses as with wind, the convective heat transfer equation is used [13]:

\[ q = h_c A_s (T_s - T_{air}) \]  \hspace{1cm} (3)

Where;
- \( q \): Heat energy (W).
- \( h_c \): Convective heat transfer coefficient (W/m\(^2\).K).
- \( A_s \): Surface area (m\(^2\)).
- \( T_s \): Surface temperature (K).
- \( T_{air} \): Ambient air temperature (K).

The heat transfer coefficient varies with wind speed. To find the air temperature \( T_{natural} \) (no wind effects) which causes the same rate of convection heat loss as \( T_{total} \) (with wind effects) the equation can be rewritten:

\[ q = h_{natural} A_s (T_s - T_{natural}) = h_{total} A_s (T_s - T_{total}) \]  \hspace{1cm} (4)

This simplifies to:

\[ T_{natural} = T_s - \left( h_{total} / h_{natural}\right)(T_s - T_{total}) \]  \hspace{1cm} (5)
$T_{\text{natural}}$: Outside air temperature with wind speed equal zero (no wind effect)

$T_{\text{total}}$: Outside air temperature with wind speed $= V_{\text{actual}}$.

$h_{\text{natural}}$: Natural convection heat transfer coefficient with no wind $= 3.5 \text{ W/m}^2\cdot\text{K}$ [14]

$h_{\text{total}}$: Total heat transfer coefficient ($h_{\text{forced}} + h_{\text{natural}}$).

The convective heat exchange at an external building surface due to air flow along the surface $h_{\text{forced}}$ is usually modelled by convective heat transfer coefficients; $h_{\text{forced}}$ can be calculated through this equation; [15].

\[
h_{\text{forced}} = 5.01(U_{10})^{0.85} \text{ for } WW
\]
\[
h_{\text{forced}} = 2.27(U_{10})^{0.85} \text{ for } LW
\]

Where;

$h_{\text{forced}}$: Forced convective heat transfer coefficients for exterior building surfaces.

$U_{10}$: Wind speed at a height of 10m above the ground, which is the typical arrangement for weather station anemometers.

WW: Windward incidence angles from -90 to 90.

LW: Leeward (remainder of incidence angles). Where incidence angles is the angle between approach flow wind direction and the normal to the windward surface.

Exterior total convection heat transfer coefficient can be expressed as a quadratic summation of natural and forced convection components [16]:

\[
h_{\text{total}} = \left[h_{\text{forced}}^2 + h_{\text{natural}}^2\right]^{0.5}
\]

Where;

$h_{\text{total}}$: Total (forced + natural) exterior convective coefficient.

$h_{\text{forced}}$: Forced exterior convective coefficient.

$h_{\text{natural}}$: Natural exterior convective coefficient.

Wind data were recorded at $\sim 4m$ from the ground ($z_0$), so to find the equivalent wind speed at a 10m height ($z$) the logarithmic law is used [17]:

\[
\frac{u(z)}{u(zr)} = \frac{m(z)}{m(zr)}
\]

Where;

$u(z)$: Wind speed at 10m height.

$u(zr)$: Available wind speed at 4m height (anemometer height over the building).

$z_0$: Surface roughness (Few trees $z=0.1m$ [17]). The landscape for the University of Newcastle, Australia.

For a height of 10 metres, $U_{10} = 1.661 \times U_4$ (at 4m height)

Note: Speed at 10meter height equals 1.661 times the wind speed recorded on top of the modules (i.e. anemometer location).
CFD has been used to analyse the modules for a long period by including the wind effect into the external air temperature surrounding the building [18, 19] by applying the above equation to the new external layer surrounding the building as shown in Figure 4.

![External air temperature](image)

**Figure 4.** New external air layer used to include wind effect in the CFD simulations.

CFD analyses were run for each module using the outside air temperature $T_{\text{natural}}$ which includes wind effects and causes the same rate of convection heat loss as $T_{\text{total}}$ (with wind effect). The simulation results were then compared with the real data [20, 23].

## 5 Results and Discussion

By comparing the number of hours that each module falls within the temperature difference (range) between the CFD simulation and the real internal air temperature as shown in Table 2, it is clear that applying wind to the external layer surrounding the modules will result in a more accurate internal air temperature calculation, where more than 90% of the simulated CFD results fall within 0-3°C compared to the real data (91% for CB, 99% for InsCB, 94% for InsBV, 93% for InsRBV modules).

**Table 2.** Percentage of the number of hours for each temperature difference between real data and CFD simulation for the analysed period.

| Temperature Range (°C) | Cavity Brick Module | Insulated Cavity Brick Module | Insulated Brick Veneer Module | Insulated Reverse Brick Veneer Module |
|------------------------|---------------------|-------------------------------|-------------------------------|--------------------------------------|
| 0-1                    | 36%                 | 51%                           | 42%                           | 32%                                  |
| 0-2                    | 67%                 | 84%                           | 80%                           | 74%                                  |
| 0-3                    | 91%                 | 99%                           | 94%                           | 93%                                  |
| 0-4                    | 99%                 | 100%                          | 100%                          | 100%                                 |

Neglecting wind effects will lead to imprecise results compared with the results when wind effects were included. The accuracy of the results reduced when wind effects were neglected as shown in Table 3. When wind effects were included, more than 90% of the results were within 0-3°C of the observed temperatures, but when the wind effects were ignored, the results drop to 83-88% compared to the real data. This illustrates the significance of including wind effects in accurately simulating the thermal performance of the modules.
Table 3. Percentage of the number of hours for each temperature difference between real data and CFD simulation for the analysed period (neglecting wind effect).

| Temperature Range (°C) | Cavity Brick Module | Insulated Cavity Brick Module | Insulated Brick Module | Insulated Brick Veneer Module | Reverse Brick Veneer Module |
|------------------------|---------------------|------------------|----------------------|-----------------------------|--------------------------|
| 0-1                    | 33%                 | 48%              | 40%                  | 30%                         |
| 0-2                    | 62%                 | 77%              | 76%                  | 69%                         |
| 0-3                    | 87%                 | 88%              | 85%                  | 83%                         |
| 0-4                    | 93%                 | 96%              | 97%                  | 99%                         |

Applying wind effect to the external air temperature layer allows larger time step sizes to be used (60, 80 or 100 minute time step size) and the CFD simulation process will take shorter computing times as shown in the Table 4.

Table 4. Computing time for different time steps.

| Time step (minutes) | Computing time for one week | Computing time for 30 days | Computing time for a season (120 days) |
|---------------------|-----------------------------|---------------------------|---------------------------------------|
| 60                  | 30 minutes                  | 1 hour 52 minutes         | 7 hours 13 minutes                    |
| 80                  | 23 minutes                  | 1 hour 25 minutes         | 5 hours 26 minutes                    |
| 100                 | 20 minutes                  | 1 hour 9 minutes          | 4 hours 22 minutes                    |

Including wind effect with the external air temperature considerably reduces the computing time and facilities the use of CFD simulations to analyse building performance over long periods.

6 Conclusions

The building internal air temperature can be calculated by adopting a new external air temperature $T_{natural}$ which takes into account the same rate of convection heat losses created by the wind surrounding the building. Therefore, $T_{natural}$ enables the direct inclusion of the wind effect and considerably decreases the overall computing time.

The paper has presented simulation results, carried out for one week in January 2010 (i.e., summer in southern hemisphere) and compared these results with real data obtained from housing test modules on the University of Newcastle campus. The results showed that the simulation time was significantly shorter whilst maintaining a high level of accuracy; more than 90% of the simulated CFD results fell within 0-3°C compared to the real data. The new technique (which can be applied to any building type with high precision) reduced the computing time for the one week analysis on a desktop PC from more than 3 years to less than 30 minutes, thus illustrating its effectiveness.

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