

VALIDATION AND PARAMETRIC ANALYSIS OF ENERGYPLUS: AIR FLOW NETWORK MODEL USING CONTAM

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ABSTRACT

An assessment was made of the use of the EnergyPlus air flow network model to predict ventilation rates in an occupied building. Parametric analyses of both the EnergyPlus air flow network model and CONTAM were conducted in parallel. Experimental measurements of an elementary school building's ventilation rates were assessed throughout the year using metabolic CO₂. The school's external environmental conditions and occupant behavior were monitored over 1 year, and used as simulation input variables. Simulated ventilation rates using the EnergyPlus network model were then validated using both measured data and CONTAM simulations. Airflow network simulations performed using EnergyPlus and CONTAM were shown to predict similar CO₂ classroom concentration levels, with an RMS of 0.89. An improvement to the EnergyPlus crack model was proposed that includes the effect of differences in zone air densities due to temperature differences.

INTRODUCTION

Carbon dioxide build up in class rooms is known to reduce the ability of students to concentrate, and influence absenteeism (Daisey 2003, Shendell et al. 2004). Suggestive evidence also links low ventilation rates with student work performance (Wargoeki et al, 2005).

Studies in the UK have shown that many schools, including buildings built to 2004 building standards, are not achieving recommended levels of ventilation. The Building Research Establishment studied internal air quality (IAQ) of eight schools across the UK (BRE 2006). This report showed ventilation levels below 3 l/s in all of the measured schools, and found 60% experienced average CO₂ levels of above the recommended concentration of 1000ppm.

A key contributor to the energy losses of modern school buildings are the ventilation losses caused by

intentional venting of class rooms to improve air quality. Energy is the largest controllable outgoing in running school buildings (Dept. of Energy 1991). Teachers often use windows and fans to improve the air quality in classrooms. This leads to a conflict of interest between the need to improve energy efficiency and the requirement of a safe and comfortable learning environment..

Designers of hybrid and naturally ventilated buildings, which often include schools, need reliable ventilation and energy performance tools if the dual goals of improved IAQ and energy efficiency are to be achieved. Building energy simulation software such as EnergyPlus and ESP-r combine the ventilation modelling of a network flow model with thermal energy simulation. As thermal effects influence the performance of natural ventilation systems, and ventilation performance impacts building energy performance, logic dictates that the combination can provide both more realistic building thermal performance and improved ventilation prediction.

In an air flow network model, the building is treated as a collection of nodes representing zones in the build and flow elements representing cracks, doors, ducts and other flow paths between the zones. Conservation of mass flows between the zones generates simultaneous nonlinear equations which can be solved to determine the resultant flow through the building. Figure 1 shows a three zone air flow network model, with windows and doors as flow path ways.

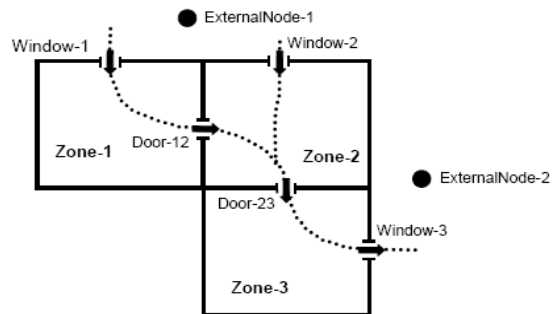


Figure 1. Simple air flow network.

Using a network model to predict ventilation rates in a building allows the inclusion of external weather data in the calculation. The natural variability of the ventilation drivers such as wind speed and direction and thermal effects can be incorporated into the calculation, providing more realistic ventilation predictions than using a fixed ventilation rate based on open window area alone.

CONTAM has been extensively validated (Emmerich 2001, Haghighat 1996) and provides an intuitive user interface that can be used to build an airflow network.

EnergyPlus has been extensively validated using a range of analytical, comparative, sensitivity and empirical tests. Independently published test suits are commonly used to verify releases. The results of these tests show good agreement with existing established simulation tools such as DOE-2.1E, IES Apache Sim and ESP-r. (Witte 2001) However these test cases do not test the performance of the air flow network model.

The EnergyPlus air distribution system was validated by comparing model results with a large set of laboratory measurements taken at the Oak Ridge National Laboratory. Measurements of duct pressure and mass flow rate recorded in a test chamber were compared to EnergyPlus predictions. Flow rate and pressure differences were shown to be within 4.1% and 3.5%, respectively (Gu 2007). Further validation was performed against data obtained from the Building Science Lab (BSL). Again comparisons for air flow rates and temperatures within the air distribution system were performed using several test cases. Peak flow rate and pressure differences of -6.2% and 8.1% respectively were seen (Gu 2007).

A whole building energy use validation of the air flow network model has been performed using BSL data. The two story two zone model again used a forced air ventilation system. Of the four test cases studied for the period between 6/10/2004 and 8/10/2004, the simulated building energy use was not seen to deviate more than 11.6% from measured values (Gu 2007).

Validation of EnergyPlus using measured data in a controlled environment provide users with the assurance that simulations are acceptably accurate. Model to model comparative tests complement these efforts and allow validation of the EnergyPlus air flow network (EPAFN) model against CONTAM: a well established and mature application. In addition, comparative study allows the assesment of the impact of small differences in models under conditions that are more representative of the applications end use, using boundary conditions derived from measured data.

This paper presents a method of performing model to model comparisons between CONTAM and EPAFN, and shows that for an 18 zone building, predicted CO₂ concentrations are comparable with an RMS of 0.89. Differences in the implementation of models are shown to result in quantifiable differences in predicted ventilation rates.

SIMULATION STANDARDIZATION

The movements of air currents around the building are a key ventilation driver. Wind speeds in weather files are measured at meteorological stations with potentially different surrounding terrain. Historically several approaches have been used to estimate local wind speeds based on weather station wind speed measurements. EnergyPlus and CONTAM use different methods of calculating local wind speed. The scope of this study does not include the impact of these differing methods. To compensate for this difference, a correction factor must be used to standardize the models to eliminate this as a source discrepancy.

EnergyPlus wind speed calculation

In EnergyPlus the local wind speed is calculated using equation 1 below (LBNL 2007).

$$V_{ref} = V_{met} \left(\frac{Z_{boundary}}{Z_{met}} \right)^{\alpha_{met}} \left(\frac{Z_{ref}}{Z_{boundary}} \right)^{\alpha} \quad (1)$$

Where $Z_{boundary}$ = Boundary layer height [m]

Energyplus version 2.0 implements this equation using the following relationship to calculate the boundary layer:

$$\text{For } \alpha < 0.32, \quad Z_{boundary} = 60$$

For $\alpha > 0.32,$

$$Z_{boundary} = 60 + (\alpha - 0.34) \times (10800 \times (\alpha - 0.34) + 440) \quad (2)$$

This implementation was derived from the original COMIS code which was based on recommendations presented in ASHRAE 1989 (Feustel, 1998).

CONTAM wind speed calculation

The local wind speed calculation is given by (Dols 2000):

$$V_H = V_{met} \times A_o \left(\frac{H}{Z_{met}} \right)^{\alpha} \quad (3)$$

Where A_o and α are coefficients used to describe how obstructed the local terrain is.

Table 2. Terrain coefficients for wind speed calculation method used in CONTAM.

Terrain Type	Coefficient (A_o)	Exponent (a)
Urban	0.35	0.40
Suburban	0.60	0.28
Airport	1.00	0.15

Wind pressure calculation

In both EnergyPlus and CONTAM, air flowing through open windows and doors, as well as through cracks in the building envelope are simulated using Bernoulli's equation (Dols 2006, LBNL 2007).

$$\Delta P = \left(P_1 + \frac{\rho V_1^2}{2} \right) - \left(P_2 + \frac{\rho V_2^2}{2} \right) + \rho g (z_1 - z_2) + P_w \quad (4)$$

Where

- ΔP = total pressure drop between points 1 and 2
- P_1, P_2 = entry and exit static pressures
- V_1, V_2 = entry and exit velocities
- ρ = air density
- g = acceleration of gravity (9.81 m/s²)
- Z_1, Z_2 = entry and exit elevations.
- P_w = wind pressure

Wind pressures are calculated in EnergyPlus using:

$$P_w = C_p \rho \frac{V_{ref}^2}{2} \quad (5)$$

The wind pressure calculation in CONTAM (Dols 2000) uses a method presented in ASHRAE 1993.

$$P_w = \rho \frac{V_{met}^2}{2} C_h f(\theta) \quad (6)$$

$$C_h = \rho \frac{V_H^2}{V_{met}^2} = A_o^2 \left(\frac{H}{Z_{met}} \right)^{2\alpha} \quad (7)$$

The wind pressure calculations in EnergyPlus and CONTAM are based on the same equation and only differ in the way the equation variables such as local wind speed are calculated.

Standardization correction factor calculation

Wind pressure calculations are the first step in calculating ventilation rates through openings in the building. The A_o coefficient was modified to ensure

predicted wind speed inputs into the two programs were equal when using identical measure weather data.

$$V_{Contam} = V_{EnergyPlus} \quad (8)$$

$$A_o \left(\frac{H}{Z_{met}} \right)^\alpha = \left(\frac{Z_{boundary}}{Z_{met}} \right)^{\alpha_{met}} \left(\frac{Z_{ref}}{Z_{boundary}} \right)^\alpha \quad (9)$$

$$A_o = \left(\frac{Z_{boundary}}{Z_{met}} \right)^{\alpha_{met}} \left(\frac{Z_{ref} \times Z_{met}}{Z_{boundary} \times H} \right)^\alpha \quad (10)$$

FLOW ELEMENT COMPARISON

The EPAFN model has three types of flow elements: cracks, simple opening and detailed openings. CONTAM has no exact equivalent of the Detailed Opening in EnergyPlus. The Simple Opening is mathematically equivalent to CONTAM's two way flow with one opening model.

Cracks are small tight air flow pathways such as the gaps around closed windows or doors, or through small gaps in the building fabric. The volume flow rate is given by the powerlaw model, where Q is the volume flow rate, C the flow coefficient and n the flow exponent (Dols 2006, LBNL 2007).

$$Q = C \times \Delta P^n \quad (11)$$

Doors and windows that open fully are described as simple vertical openings. It is assumed that the velocity of the airflow as a function of height is given by the orifice equation (LBNL 2007):

$$V(y) = C_d \sqrt{2 \frac{P_n(y) - P_m(y)}{\rho}} \quad (12)$$

Where V(y) is velocity of the airflow, ρ is the density of air, C_d is the discharge coefficient, P_n and P_m are the reference pressures of the zones either side of opening.

COMPARISON VALIDATION

The complex nature of building simulation allows several opportunities for errors to occur during preparation of the initial experimental conditions. The initial validation exercise was performed to ensure all of the initial simulation parameters in both CONTAM and EnergyPlus were identical, and to establish that comparable flow elements can be defined in both EnergyPlus and CONTAM.

Building test case

A rectangular test building with a ratio of approximately 4:1 was constructed in both EnergyPlus and CONTAM. Figure 2 is the CONTAM airflow network model containing two flow elements, one in the north and one in the south wall.

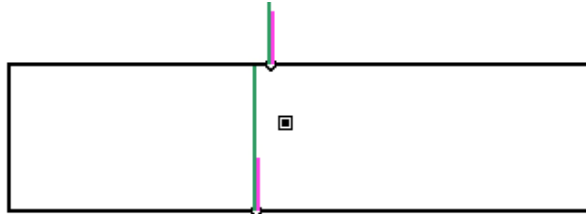


Figure 2. Building test case flow paths.

Wind Pressure Coefficients

TNO, the Dutch building research institute (TNO 2008) provides a web based interface to its software to calculate wind pressure coefficients of buildings. The coefficients used in this test building and the final school simulation were generated using TNO's software.

Flow element validation

Using the rectangular test building, simulations were performed in EnergyPlus and CONTAM under steady state conditions to compare the performance of each comparable flow element type. Weather files for each application were modified to simulate constant: temperature at 20 degrees, atmospheric, relative humidity, and a constant wind 6 m/s due North.

The power law ventilation model given by equation 11 is the least complex of the described models. Under constant identical weather conditions, the mass flow rate through cracks predicted by Contam and EnergyPlus are effectively identical, differing by only 0.09%.

Under identical conditions, Contam and EnergyPlus predictions for simple openings differ by 0.54%. A difference of 0.54% for open window ventilation predictions, and 0.09% difference between flows from cracks are acceptably low to allow a complete building airflow network comparison.

The performance of the two flow element models was studied using a weather file generated from measured, two-minute weather data. Figure 3 shows test room ventilation rates over a one week period for CONTAM and EnergyPlus using simple openings, using a flow coefficient of 0.78. Weber and Kearney (Weber and Kearney 1989) have shown the default value of 0.78 to work well for most applications. Predicted ventilation rates for the two applications have an RMS of 0.62.

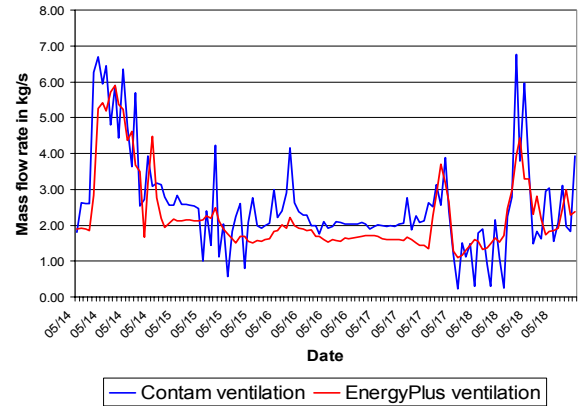


Figure 3. Simple opening test room ventilation comparison in kg/s.

Crack flow element results were compared. Figure 4 shows ventilation rates for the test room using a flow coefficient of 0.01 and exponent of 0.5 using real weather data. A significant difference between model predictions was found. By altering the weather file to set external and internal zones to be in thermal equilibrium, it was shown that the difference in ventilation flow rates was due to the effect of temperature differences between the outside and inside.

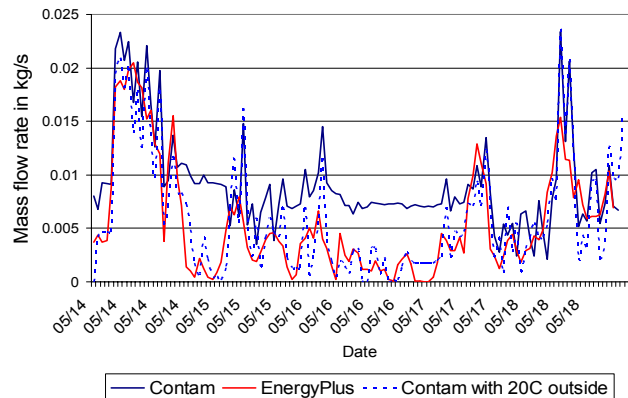


Figure 4. Crack test room ventilation comparison in kg/s.

When the CONTAM simulation is performed under constant 20 degrees C external temperature, the RMS difference when compared to EnergyPlus was 0.7 compared to 0.55 using measured temperatures.

Window number study

The school classrooms in the monitored building have 8 individual bucket type windows of identical cross-sectional area. A study was conducted in CONTAM to establish whether the eight windows would need to be modeled individually. Simulations of the test case building were performed using 1-8 small windows of 0.5m by 1.5m. The experiment was repeated using a single window of varying area equivalent to the sum of

the individual small windows, then again for a third time using one large window and varying the opening schedule over the equivalent range of open percentages. The results showed that there was no difference between using varying window area and its equivalent scheduled percentage open. Using several smaller windows did produce a 2% difference in results compared to a single window of equivalent area.

Measurement of school environment conditions.

Sensors were used to monitor external and internal environmental conditions, and the building’s heating demand. The behavior of the building occupants that impacts on the building heating load, such as usage of extractor fans and opening of windows was also logged. The internal environmental variables measured in the classroom include the dry bulb temperature, CO₂ concentration and humidity levels. A Davis Pro 2 weather station was used to monitor the external horizontal irradiation, wind direction / speed, rain fall and barometric pressure. Sensors were located throughout the building, focusing on two main classrooms where CO₂ sampling occurred.

Alarm sensors on the two window classrooms provide a detailed picture of window opening behavior. These measurements were translated in window opening schedules to be used in the building simulation. Figure 5 shows window opening behavior for one week.

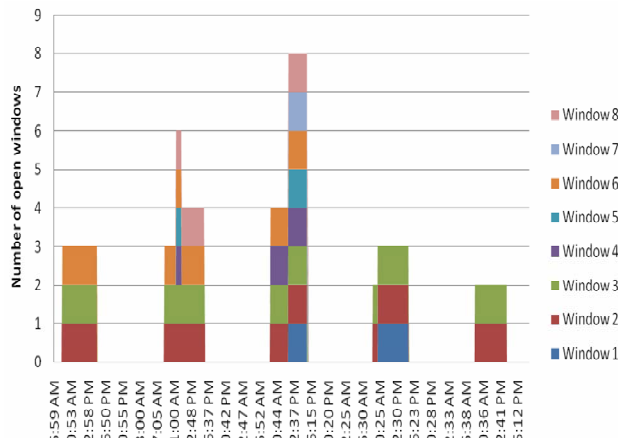


Figure 5. Week beginning 24th of April window opening behavior.

Figure 7 shows an example of CO₂ measurement data taken over a five week period. Figure 6 shows the corresponding window state. CO₂ levels can clearly be shown to exceed the recommended guideline limit of 1000 ppm for sixteen of the twenty five days shown. Despite this, windows are only all opened for a single period during one of the twenty five days. A direct correlation can be seen between the week with the

highest CO₂ concentration levels and the week with the lowest number of open windows, shown as the second week in Figure 6.

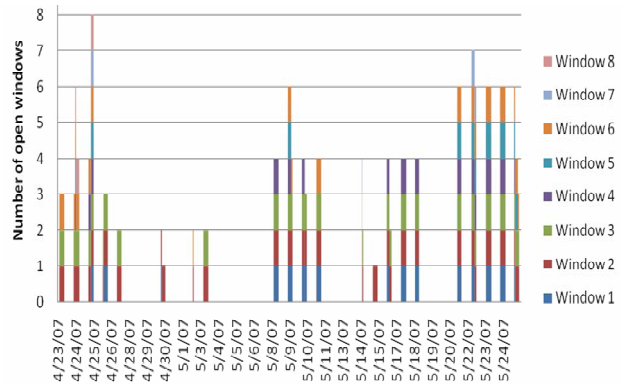


Figure 6. Five week window opening behavior beginning 23/4/07.

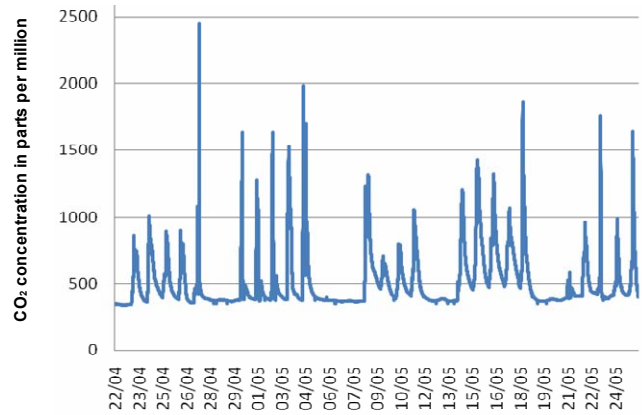


Figure 7. Carbon dioxide concentration over 5 week period beginning April 22nd.

Analysis

Ventilation rates were calculated based on experimental measurements of carbon dioxide concentration. Figure 8 shows the CO₂ decay profile for one day during an unoccupied period, against the open window count.

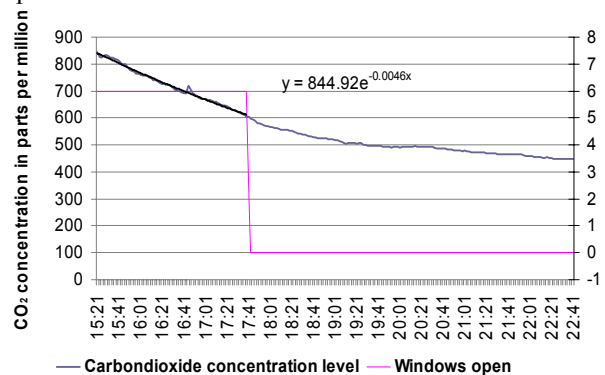


Figure 8. CO₂ decay profile of classroom with 6 open windows.

Calculations of ventilation rates were performed repeatedly under different window opening scenarios. In a well mixed room, the concentration of CO₂ in the room will decrease exponentially. The gradient of the natural log of this curve gives the air change rate, which can be converted to an absolute ventilation rate for a room of known volume. Table 3 shows the average measured ventilation rate for zero to six open windows.

Table 3. Average measured ventilation rate for 0 to 6 open windows.

NUMBER OF OPEN WINDOWS	VENTILATION RATE IN KG/S	NUMBER OF AVERAGED SAMPLES
0	0.0038	8
4	0.0061	4
6	0.0079	3

The number of decay curve samples was limited by the number of occasions when windows were left open, without occupants, for long enough periods for a valid decay exponent to be determined. Ventilation rates derived from CO₂ measurements were used as a guide in the final building simulations to calibrate window flow element coefficients. An outside CO₂ concentration of 430ppm was assumed for all calculations based on averaged measured morning values.

AIR FLOW NETWORK SIMULATION

A complete air flow model of the school was created in both EPAFN and CONTAM. Figure 9 shows the school air flow network with inter-connecting flow elements, representing windows, doors and cracks. The top half of the building contains the classrooms that form the basis of the study, and are therefore modeled in greater detail.

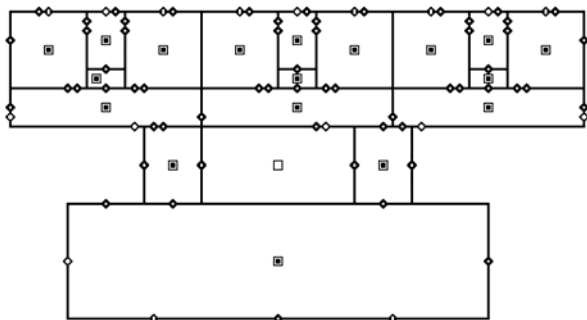


Figure 9. School air flow network.

A simulation study was conducted of the classroom ventilation rates, given the following real measured environmental data: weather data, including external pressure, temperature, solar radiation, wind speed and direction; student occupancy data from classroom registry; and window opening data from sensors.

Local weather file creation

The comparison between simulated and measured necessitated the creation of a local weather file from the weather station installed on the roof of the building eight meters from ground level and four meters from the building's roof. Building simulation software such as EnergyPlus requires both diffuse and direct components of solar radiation to be present in a weather file. As measurement of direct radiation data was not possible, the diffuse and direct components of the measured data were calculated using a mathematical model, Dutton et al (2008) which showed that for this location Maxwell's (Maxwell 1998) diffuse ratio model was the most suited for estimating radiation ratio data for building simulation calculations.

Simulation setup

Windows and doors were modeled as Simple Openings and Two Way Flows in EnergyPlus and Contam, respectively. Each window flow element was given an opening schedule generated from window opening data measured. The number of students from twice daily registration was used to estimate the metabolic CO₂ generated in the classroom. It was estimated that the exhaled CO₂ by each child age 8-10 was 50% of the normal adult rate for sedentary work of 0.3 liters per minute.

Equation 13 was used to estimate the CO₂ level as an alternative to solving the mass balance differential equations.

$$C_t = \left[\frac{QC_{ext} + q}{Q} \right] \left[1 - e^{-\frac{Qt}{V}} \right] + C_0 e^{-\frac{Qt}{V}} \quad (13)$$

Ventilation rates used in equation 13 were simulated using EnergyPlus and CONTAM, over a range of input parameters.

Ventilation simulation results

The school building air flow was simulated with CONTAM and EnergyPlus, using measured window usage and on site weather data. The simulation models were then calibrated using measured ventilation rate data. Table 4 details the flow coefficients used to define the building's flow elements. Internal flow coefficients are based on estimates within boundaries

set by Ivy et al (Ivy 2001). Window coefficient values were calculated from measured window ventilation rates, which were derived from measured CO₂ data.

Table 4. Flow element coefficients.

FLOW ELEMENT	COEFFICIENTS
Class window	Area 4.5 msq, Dis. Coeff. 0.01, exponent 0.5
Extern. class wall crack	C=0.04, n=0.5
External wall crack	C=0.01, n=0.5
Internal door crack	C=0.015, n=0.5
Internal wall crack	C=0.01, n=0.5

Figure 10 shows the ventilation rate of a sample classroom as predicted by both applications. Ventilation mass flow rates given have an RMS of 0.75.

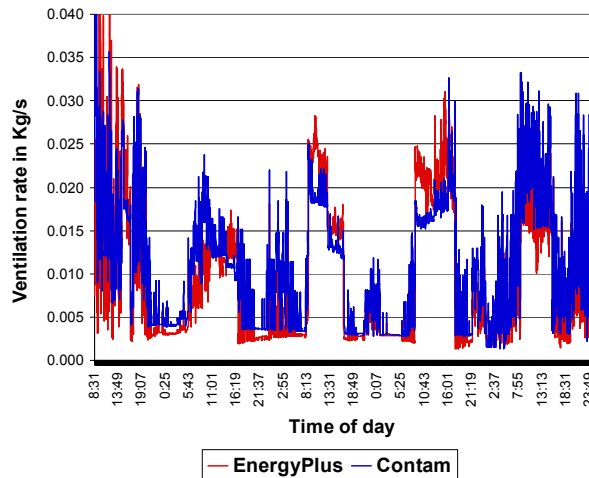


Figure 10. Ventilation rate comparison.

Analysis of the ventilation data shows that during periods of closed windows when crack ventilation dominates, EnergyPlus results consistently give lower ventilation predictions. This was determined in previous studies to be a result of differences in the implementation of the crack model relating to zone temperature differences. The impact of this difference can be seen in predicted CO₂ concentrations shown in Figure 11.

Comparison between measured CO₂ concentration levels and simulated results

Using equation 13, CO₂ concentrations were calculated from ventilation rates and recorded occupancy. Comparisons with measured data showed an RMS of 0.59 for CONTAM and 0.54 for EnergyPlus. The decay of the second peak shown in figure 11 was representative of the data set where EnergyPlus CO₂ concentration estimates are exaggerated by morning of the next day. This is consistent with preceding studies

that showed reduced EnergyPlus crack ventilation rates.

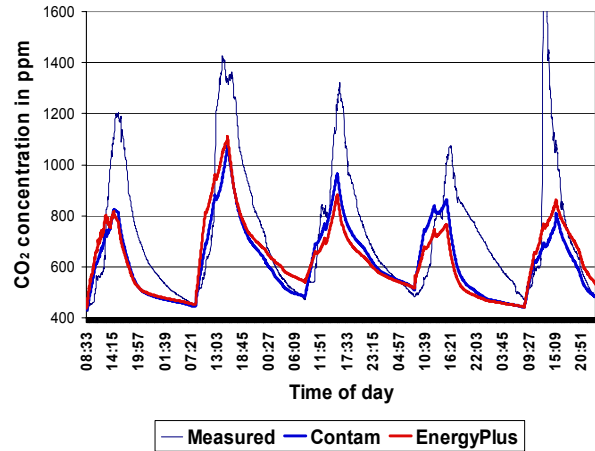


Figure 11. CO₂ concentration prediction comparison.

Improvements to the EnergyPlus crack model would improve the accuracy of IAQ calculations. However, despite their differences the EnergyPlus and CONTAM predictions when compared to each other had an RMS of 0.89.

CONCLUSION

The study showed that airflow network simulations performed using EnergyPlus and CONTAM predict similar CO₂ classroom concentration levels, with an RMS of 0.89 when thermal gains are eliminated and wind speed input coefficients are adjusted to compensate for model differences. Improvements to the EnergyPlus crack model to include flows driven by the air density differences between the zones would improve the accuracy of IAQ calculations.

Comparisons with measured data are limited at this stage as no measured data exists to calibrate the internal flow element variables. Using estimated internal flow coefficient values CONTAM and EnergyPlus gave RMS values of 0.59 and 0.54 respectively, when compared to measured data.

Future work will involve a correlation analysis of measured input parameters to the measured CO₂ data. These results will be compared to a similar correlation analysis of the simulation input parameters to the resultant simulated CO₂ concentration. Further experimental measurements of building element ventilation rates could be used to better calibrate simulations, allowing direct comparisons to simulated data to be made.

An improved EnergyPlus crack model could be developed and shown to give improved CO₂ concentration predictions.

NOMENCLATURE

V_{ref} = Reference wind speed at local height.

$Z_{boundary}$ = Boundary layer height.

Z_{ref} = Reference height used for wind pressure coefficient data

α_{met} = Wind velocity profile exponent at met. station.

α = Site wind velocity profile exponent

V_H = Wind speed at the building height

V_{met} = Wind speed at meteorological station

H = Wall height

A_o, α = Constants relating to the local terrain

Z_{met} = Meteorological station height (fixed to 10m)

P_w = Wind surface pressure relative to static pressure in undisturbed flow [Pa]

P = Air density [kg/m³]

V_{ref} = Reference wind speed at local height [m/s]

C_p = Wind surface pressure coefficient.

C_t = Indoor concentration [g·m⁻³] of CO₂.

Q = Ventilation rate of outdoor air [m³·s⁻¹].

C_{ext} = Concentration of CO₂ outdoor air [g·m⁻³].

C_0 = Initial indoor CO₂ concentration [g·m⁻³].

q = Mass indoor emission rate of CO₂ [g·s⁻¹].

q' = Volumetric indoor emission rate of CO₂ [m³·s⁻¹].

V = Volume of the indoor space [m³].

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