IMPACTS OF INFILTRATION/EXFILTRATION FROM WIND, STACK AND BUOYANCY IN A/C DESIGN - AN ENERGYPLUS ENERGY SIMULATION CASE STUDY

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ABSTRACT

Infiltration is rarely considered a critical factor in AC design. Purposed built buildings such as libraries or shopping centres with dynamic occupants may prove otherwise. The main access to Macquarie University Library is through three large doors in the foyer. Infiltration/exfiltration rates through these doors warranted a careful analysis for its HVAC design and sizing. The Airflow Network model in EnergyPlus was utilised to simulate the bulk air flow throughout the whole building driven by the inflow/outflow through these doors with wind-tunnel-tested wind pressure coefficients. Compared with the model without infiltration modelling, the cooling energy in the foyer exceeds it by almost an order of magnitude and significantly more for heating energy due to sensible heat loss in winter. The infiltration/exfiltration energy component alone made up around 13% of the total annual building AC energy.

INTRODUCTION

Basic concepts and rationale

Ventilation and to a certain extent, infiltration are used to provide outdoor air through a building for dilution and removal of indoor air contaminants. The energy requirement for outdoor air conditioning can be a significant portion of the total space conditioning load of the building. For proper sizing of the HVAC equipment and thermal loads analysis, the magnitude of outdoor air flow and its impact on the building air distribution system as a whole must be quantified.

While ventilation is about intentional introduction of outdoor air into the building for indoor air quality purposes be it by mechanical or natural ventilation, infiltration is associated with the uncontrolled flow of outdoor air into a building through normal use of exterior doors for entrance or egress, other inadvertent openings and cracks. Exfiltration is on the contrary the leakage of indoor air out of a building. The manifestation, domination and interaction between these different modes must all be considered and accounted for in the proper design and operation of a HVAC system.

To meet the fresh air requirement of the occupants as prescribed in ASHRAE Standard 62 or AS 1668, HVAC designers usually rely on mechanical or forced ventilation in a typical mechanical cooling for a closed building ventilation system. Natural ventilation through operable windows by the occupants is dependent on weather and building envelope and can sometimes impose large energy penalty especially in a mixed mode ventilation system. Infiltration if left unaccounted for may have a large energy impact in commercial and institutional buildings especially in tall, leaky and under-pressurised buildings.

Often used interchangeably, infiltration and air leakage are different with the latter being a measure of the air tightness of the building form/shell but the two have a proportionality relationship in the sense that when air leakage area is larger the infiltration rate will increase proportionally. Whilst infiltration can be reduced to some degree for example by reducing the surface pressures caused by the wind through strategic landscaping or use of wind barrier and stack pressures through increase of air flow resistance between floors, the infiltration rate of a building is strongly dictated by weather conditions such as wind speed and direction, equipment operation (doors or windows predominantly) and occupant activities. Typical infiltration rates can vary from 0.2 ACH to 2 ACH for a tightly and loosely constructed housing.

In this study, a large institutional building with its primary use as library has three doors used to enter and exit the building. Due to its frequent operation the doors are exposed to significant infiltration or exfiltration rates. To quantify this energy impact, a comprehensive full year simulation incorporating detailed building modelling equipped with all internal and external openings, cracks and the interconnected air space between rooms was conducted. The wind pressures working on the doors were measured through a wind tunnel test and the Wind Pressure Coefficients were used as input into the energy model. The infiltration heat gain and loss as well as the cooling and heating energy consumption for the zone, the AHUs and the whole building were quantified in a sub-hourly time step simulation and the results were compared with another scenario where infiltration from those doors was not considered under the same weather conditions. It was found that the energy impact from the operation of those library doors was too great to overlook and needed to be factored in the design and equipment sizing of the HVAC equipment.

Case study descriptions

Macquarie University Library is a multi-level building of 5 storey height totalling approximately 20,000 sqm floor area. The building facade has a large number of intricate external shading devices. The main access to the library is through the three doors on Level 2 - Foyer, each measuring 3.5 m in height and 2.2 m in width. It is through these three doors where library patrons access and exit the building that external conditions in wind speed and direction, stack and buoyancy were being investigated for their impacts on the heat balance and air flow inside the building.

Building

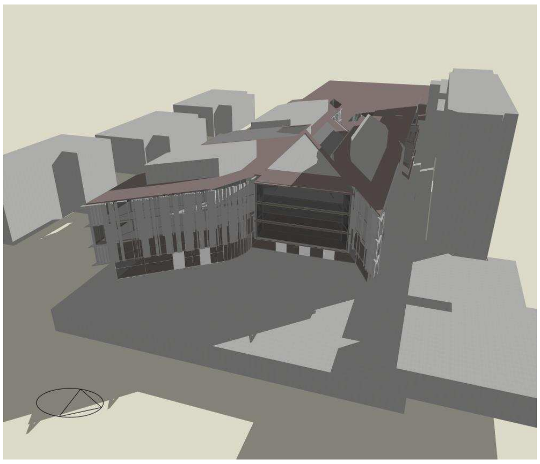

Figure 1. Eastern view of the library building.

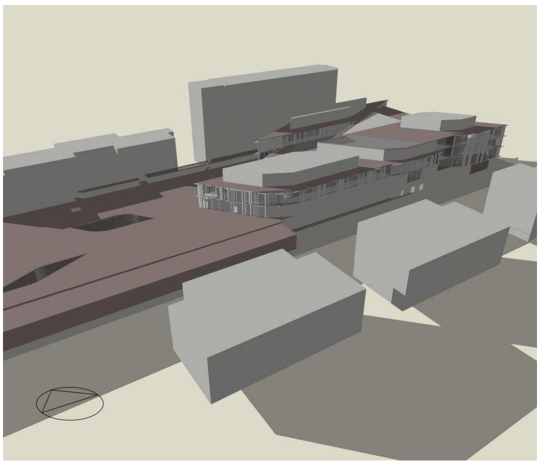

Figure 2. Southern view of the library building.

Level 2

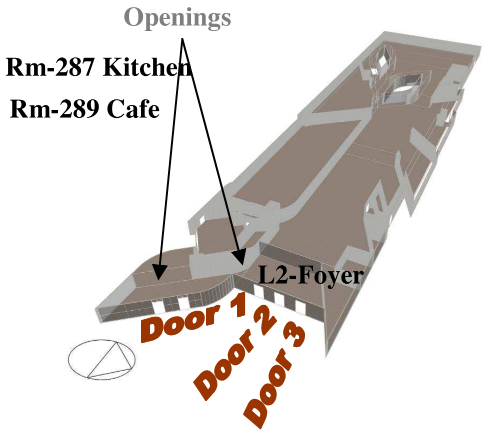

Figure 3. Rendered view of Level 2 floor plan showing the three doors and zones connected by air space.

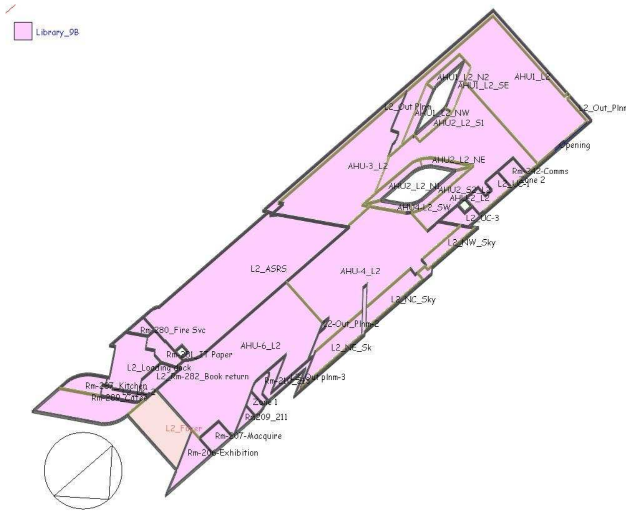

Figure 4. Level 2 floor plan.

Level 2 - Foyer

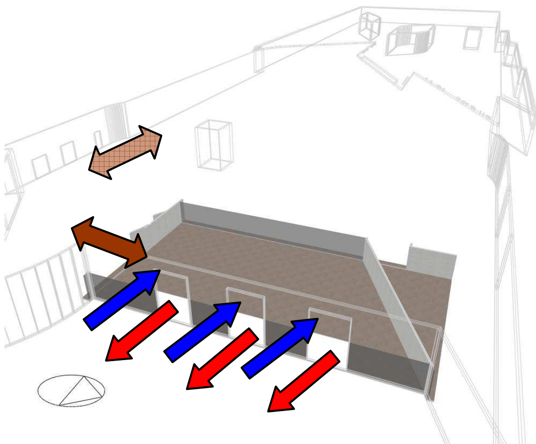

Figure 5. Air flow through doors with exposure to external conditions and internal flow interaction between zones.

HVAC system - main and supplementary

The HVAC system consists of a single duct VAV air terminal with electric reheat. Water cooling coils are installed in 26 AHUs and 15 FCUs. A zone reheat electric coil is placed in supply duct for each conditioned zone.

A rotary type (wheel) air to air sensible and latent heat recovery (HR) unit is placed upstream the outdoor air mixing box for all the AHUs (except AHU26). The effectiveness of the sensible and latent heat recovery units is assumed to be 65%. The FCUs have no heat recovery function.

The chiller is an electric Trane CVHF 2567 kW unit represented with an empirical model that uses performance information at reference conditions along with three curve fits for cooling capacity and efficiency to determine chiller operation at off-reference conditions. The condenser is water cooled served by a variable speed cooling tower.

METHODOLOGY

Simulation procedures

The infiltration modelling with Air Flow Network (AFN) multi-zone started with geometry creation for the building in DesignBuilder. The building geometry was prepared and set up for the air flow network modelling to analyse dependence of air flow on wind pressure, buoyancy and stack effects in EnergyPlus. Certain requirements have to be followed to enable proper set up of the model so that the model structure conforms to AFN modelling in EnergyPlus. At this stage, all other aspects of the building and its energy consumption including occupant loads, building fabric, lighting loads, HVAC systems had to be defined as well.

Following this, the building model was exported into the EnergyPlus idf format. This is where the next level of set up was performed where detailed objects and components were defined, input definitions were checked and fine tuned, scopes and thresholds for variables and parameters were verified, connectivity and integrity of systems, loops, branches, nodes were checked and tested as well as output set up was carried out as required.

Then, the library doors of interest were identified and their opening schedules were incorporated in the relevant object fields along with the wind pressure coefficients from the wind tunnel test data into the appropriate EnergyPlus component. Steps that followed include identify, check and close off other openings that were not supposed to be open.

Following on was clarification of output variables and allocation of an appropriate weather file before running the calculation.

Afterward, results were collected, filtered and analysed for inclusion in the report.

Energyplus energy simulation software

EnergyPlus is a modular, structured energy simulation software based on the most popular features and capabilities of BLAST and DOE-2.1E. A simulation engine with simple input and output text files, EnergyPlus is designed to provide an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction. EnergyPlus has two basic components—a heat and mass balance simulation module for loads calculations and a building systems simulation module to calculate heating and cooling system and plant and electrical system response and also to communicate with various HVAC modules such as coils, boilers, chillers, pumps, fans etc and the HVAC air and water loops mimicking the network of pipes and ducts found in real buildings.

The EnergyPlus software version 3.1.0.027 was used to perform infiltration modelling on Macquarie University Library to assess the inflow/outflow rate of outdoor air coming through the main entry doors on Level 2 from the library patrons opening or closing the doors taking into account effects imposed by external weather such as wind speed and direction as well as buoyancy and stack.

Natural ventilation modelling using air flow network (AFN)

Natural ventilation can be simulated using the Airflow Network model in EnergyPlus. The multi-zone AFN provides the ability to simulate multizone airflows in a building through cracks, openings, windows and doors in exterior or interzone surfaces driven by wind, buoyancy or stack effect and also by a forced air distribution system when air distribution is modelled.

Excluding air distribution modelling, the multi-zone AFN model has the capabilities to also simulate and calculate:

- Multizone airflows due to forced air, wind, and surface leakage, including adjacent zones and outdoors, during HVAC system fan operation or when the system fan is off
- Zone pressures due to envelope leakage driven by wind when the HVAC system fan is off or if no air distribution system is specified
- Allow zone exhaust fans inclusion as part of the airflow network and its impact on air flows, pressures, air temperatures, humidity levels and energy consumption
- Natural ventilation (i.e., air flow through open or partially open exterior windows and

doors) with zone level control or individual surface control for a subsurface (window, door, or glassdoor) with modulation control and air flow through cracks in exterior or interzone surfaces, around closed windows or doors.

- Dependence of air flow on buoyancy effects and wind pressure that is governed by wind speed, direction and surface orientation,
- Bi-directional flow through large vertical openings.

Modelling limitations

1. Air circulation and/or air temperature stratification within a thermal zone with a high space such as an atrium should not be divided into subzones separated by artificial horizontal surfaces that have cracks or openings. AFN modelling in this scenario will not give a realistic temperature and air flow in each subzone and/or between subzones.
2. The model is restricted to eleven specific types of coils to suit the air distribution system. The types of coils selected for the HVAC system and used in the simulation are from the approved list.
3. Exclusion of air distribution system modelling to account for supply and return air leaks, duct leakage, air flows and pressures in ducts or other components in the air distribution system.

Theories and Assumptions

Wind pressure calculations

The wind pressure is determined by Bernoulli's equation, assuming no height change or pressure losses:

$$p_w = C_p \ \rho \ \frac{V_{ref}^{\ 2}}{2} \tag{1}$$

Linkage models

A linkage used in the AirflowNetwork model has two nodes, inlet and outlet, and is linked by a component which has a relationship between airflow and pressure. The pressure difference across each component in a linkage is assumed to be governed by Bernoulli's equation:

$$\Delta P = \left(P_n + \frac{\rho V_n^2}{2}\right) - \left(P_m + \frac{\rho V_m^2}{2}\right) + \rho g\left(z_n - z_m\right) \tag{2}$$

By rearranging the terms and adding wind pressure impacts, the above equation may be rewritten in the format used by the airflow network model:

$$\Delta P = P_N - P_M + P_s + P_w \tag{3}$$

Several assumptions were taken in the modelling as follows:

- all constraints imposed in EnergyPlus v. 3.1.0.027 were applicable.
- Sydney's weather data was used with modified wind data (wind speed and direction) supplied by an external consultant (details in Section 3.5).
- thermal comfort control not applicable.
- all external and internal openings (windows or doors), external vents and holes were assumed closed except the three external main doors in Level 2 Foyer operated with appropriate schedules.
- no modulation factor applied to the opening of the main doors.

Acquiring wind data and Wind Pressure Coefficient (WPC) values

The weather data is based on Sydney Central Business District's with modified wind climate data (wind speed and direction) for the site location carried out by Windtech. The weather station used to collect the half-hourly data for 2006 relevant to the North Ryde site location is the Sydney International Airport data corrected for the effects of height and local terrain.

The WPCs for the three main entry doors were determined from a wind tunnel test conducted in Windtech's wind tunnel using a 1:300 scale model of the proposed development including the land topography and surrounding buildings for a radius of approximately 375 metres from the subject site location. The reference building height used in the wind tunnel test was 20 m and the suburban terrain was picked from the three terrain types existing in the surrounding to be modelled in EnergyPlus. For the suburban terrain (towns and cities), the appropriate wind speed profile exponent was 0.33 and the boundary layer thickness was taken as 460 m.

Measurements were taken for 36 wind directions with 10 degrees increments with the three main openings each fitted with a pressure tap. The output from each pressure tap was then plotted and processed to produce the wind pressure coefficients for each wind direction (with reference to the velocity pressure at the building reference height). The nominal mean values of the WPCs from the wind tunnel data, tested for the three main doors is available upon request.

Base model with no infiltration modelling

The base model actually shares the same structures and everything in it with the infiltration model minus the Air Flow Network (AFN). This essentially treats the building as an isolated box with no external effects because all the doors and windows are assumed closed and no infiltration at all, not even through cracks, is modelled.

The space conditioning energy data from this second model was used to compare with those from the infiltration model to see how and to what extent infiltration/exfiltration had an impact in the overall energy consumption of the building.

Model setup

Simulation control and Multi-zone

Fundamental to the Simulation Control object is the type of simulation which for the given scope of work would be accomplished with multi-zone without distribution. The wind pressure coefficient type was set as 'input' with the wind pressure coefficients user-defined for all external sub-surfaces (windows or doors). 'Opening Height' is used in the Height Selection for Local Wind Speed Calculation field which appoints the centroids in the z direction of the AFN:MZ:Surface objects as the heights used in the local wind speed calculation.

The AFN multi-zone object required to perform AFN calculations allows control of natural ventilation through exterior and interior openings in a zone, where “opening” is defined as an openable window or door. Every zone that exists in the entire building must be defined here. The control will be applied in the same way to all of the openings in the zone. Ventilation control for all openings is provided at the zone level as default but can be overridden by individual ventilation control at a surface opening. 'Temperature' was selected as the ventilation control mode which means all of the zone’s openable windows and doors are opened if Tzone > Tout and Tzone > Tset and Venting Availability Schedule allows venting. The temperature setpoint schedule was set at 22ºC in line with occupancy hours but the Venting Availability Schedule was set to 0 to mean either the openings are closed at all times or zone level control is relinquished to surface level.

Surfaces

The AFN:MZ:Surface object allows a heat transfer surface (wall, roof, floor or ceiling) to have a crack or a sub-surface (window, door or glass door) to have an opening (detailed or simple). In other words, the numbers of cracks and openings if added will equal the number of surfaces. In the Leakage Component Name, the name of the crack or opening associated with this surface should be entered. A window, door or glass door heat transfer sub-surface must be defined with either a 'simple' or 'detailed' opening otherwise an error message will be reported.

The window/door opening factor or the crack factor is entered here. A default value of 1 is usually used. A realistic value should be used for windows or doors that are opened on schedule. The following fields of AFN:MZ:Surface object control venting. They are used only when the associated heat transfer surface is that of an openable exterior or interior window, door or glass door. Ventilation Control Mode is set as 'Temperature' by default. For an openable window or door controlled by schedule, this can be set to 'Constant' that permits venting whenever the venting availability (schedule) allows it independent of the indoor and outdoor temperatures. “Constant” here means that the size of this opening is fixed while venting but the air flow through this opening can, of course, vary from timestep to timestep.

The temperature schedule field defines a temperature above which this openable window or door will be opened if the conditions described in the previous field Ventilation Control Mode are met relevant only when the Ventilation Control Mode is set as either 'Temperature' or 'Enthalpy'.

The following five fields related to Modulation of Openings can be used to modulate this window/door opening when Ventilation Control Mode = Temperature or Enthalpy. These fields determine a factor between 0 and 1 that multiplies the opening factor of this window or door according to certain control actions. Modulation of this opening can reduce the large temperature swings that can occur if the window/door is open too far when it is venting, especially when there is a large inside-outside temperature difference. No modulation was modelled so these fields were left blank.

The last field is Venting Availability Schedule the same as that used in AFN:MZ:Zone.

Cracks and Openings

The object AFN:MZ:ReferenceCrackConditions can be left as default. All the crack objects that define external and internal surfaces will have the air mass flow coefficient at reference conditions and air mass flow exponent automatically defined during model set up. The reference crack conditions field in the AFN:MZ:Surface:Crack should have the name of the reference crack conditions object previously defined.

The AFN:MZ:Component:DetailedOpening was assigned to all sub-surfaces (windows/doors). The field for air mass flow coefficient when opening is closed shall be filled in with a value that resembles crack flow when the window or door is closed.

The AirflowNetwork model assumes that open windows or doors are vertical or close to vertical; for this reason they are called “Large Vertical Openings.” Such openings can have air flow moving simultaneously in two different directions depending on stack effects and wind conditions. AirflowNetwork models such two-directional flow, but only for vertical openings.

It is assumed that the air flow through a window opening is unaffected by the presence of a shading device such as a shade or blind on the window. Also, the calculation of conductive heat transfer and solar gain through a window or door assumes that the window or door is closed.

The AirflowNetwork model does not have a model for bi-directional flow through large horizontal openings. For this reason, AFN:MZ:DetailedOpening should not be used for horizontal openings (this restriction applies for up to EnergyPlus v.3.1).

In the type of Rectangular LVO field, choose 'Non-Pivoted' or leave it as default for the same effect. Normally, 2 sets of Opening Factor Data are minimum and enough for the definition of an opening. Opening factor in the first set starts with 0, The discharge coefficient in the next field indicates the fractional effectiveness for air flow through a window or door at that Opening Factor. The next three fields: Width Factor, Height Factor and Start height Factor can be filled according to Fig. 81 on page 806 of the EnergyPlus I/O Reference. The second and final set of opening factor data starts with Opening Factor set at 1. The rest of the fields are similar to the first set and can be set accordingly.

When the opening factor value (as described under the field Window/Door Opening Factor in the AFN:MZ:Surface object) is between two Opening Factor field values, the values of Discharge Coefficient, Width Factor, Height Factor, and Start Height Factor are linearly interpolated.

External nodes and Wind Pressure Coefficients

External nodes in the AirflowNetwork model define environmental conditions outside of the building. These conditions include wind pressure coefficients that vary from façade to façade and can be highly dependent on the building geometry.

The external node name is associated with a particular building façade. This name is referenced by the External Node Name field of an AFN:MZ:WindPressureCoefficientValues object (which gives wind pressure coefficients for the façade as a function of angle of wind incident on the façade) and by the External Node Name field of an AFN:MZ:Surface object.

In the AFN:WPCArray object, the first name field is referenced by each AFN:MZ:WindPressureCoefficientValues object which, for each AFN:MZ:ExternalNode, gives the wind pressure coefficients at each of the wind directions listed in the AFN:MZ:WindPressureCoefficientArray. This name is also referenced by the AFN:SimulationControl object. Up to 36 wind directions can be specified in the following fields.

In the AFN:WPCValues object, the field designated for WPC Array Name refers back to the relevant WPC Array object. WPC values can be obtained from wind tunnel measurements, CFD calculations, or from published values for different building shapes.

Heat Recovery Units and Zone L2-Foyer air handling unit, FCU14

A heat recovery unit was incorporated in each of the 25 AHUs (except AHU26) serving the whole building. It's the rotary wheel air-to-air sensible and latent heat exchanger type with 65% effectiveness for heating and cooling at 75% and 100% air flow. The nominal supply air flow rate of each HR unit has been pre-defined as per mechanical HVAC design requirements.

The zone L2-Foyer is serviced by a dedicated air handling unit named FCU14. This FCU is not associated with any heat recovery unit.

Opening and Closing Schedules for Doors

The three main doors to L2 - Foyer of the library are operating on a scheduled devised as follows:

During weekdays:

- 08:00am to 10:00am - open all the time
- 12:00pm to 14:00pm - open all the time
- 22:00pm to 08:00am - open 40% of the time
- All other times - open 75% of the time

During weekends & holidays:

- 09:00am to 15:00pm - open all the time
- 15:00pm to 17:00pm - open 75% of the time
- 17:00pm to 09:00am - open 40% of the time

These schedules were supplied by the library mechanical contractor and by no means exhaustive. A much more comprehensive set of schedules could be devised in the future to give doors opening and closing operation down to the minutes based on measured field data. The schedule data could be manipulated to feed from a table based on the door sensor electrical signals for example. At this stage, the dynamic nature of these doors operation was deemed satisfactory to be represented by the generic schedules above. It will be interesting to see and quantify the impacts of these schedules should the 'improved' version become available.

RESULTS AND DISCUSSIONS

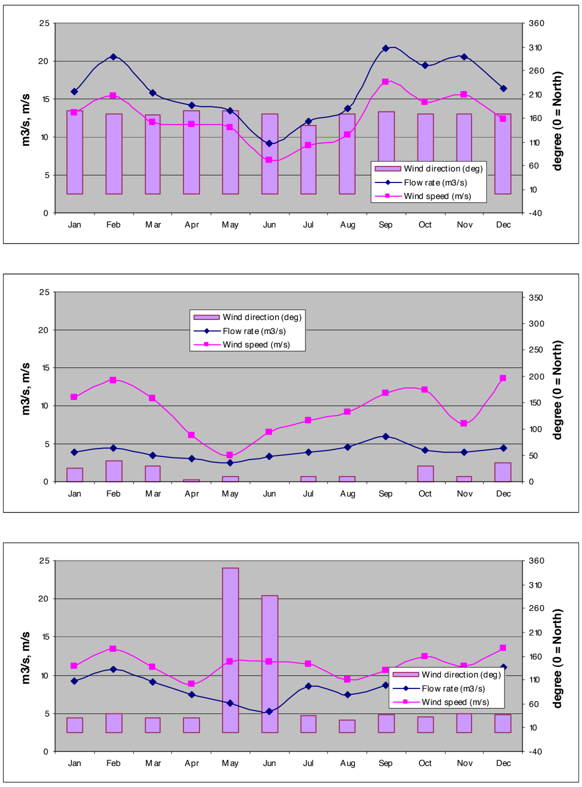

Figure6 Monthly max hourly infiltration rates of Doors 1,2 and 3 as a function of wind speed and direction

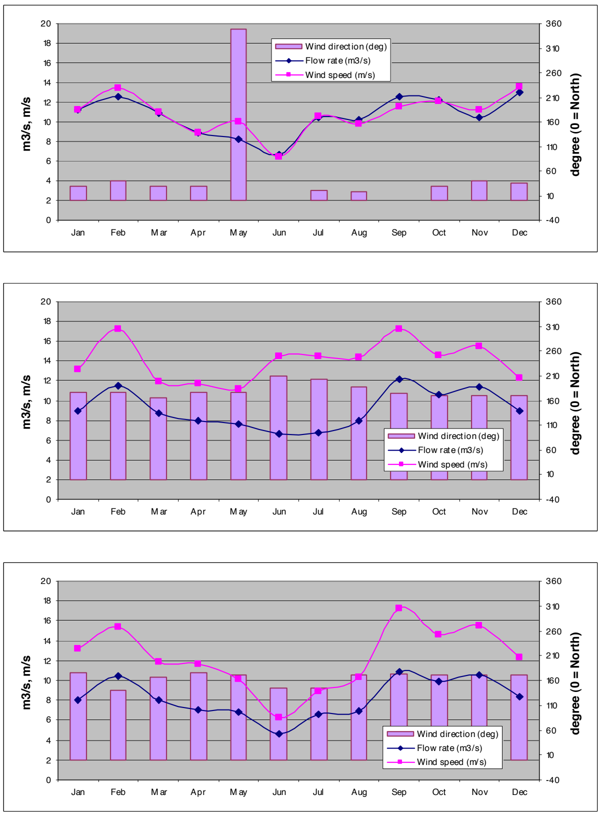

Figure7 Monthly max hourly exfiltration rates of Doors 1,2 and 3 as a function of wind speed and direction

Table 1 Infiltration sensible gain rate of L2-Foyer (infiltration modelling with AFN)

Infiltration sensible gain rate (kW); Wind speed (m/s); Wind direction (deg) (date, time)		Jan	Feb	Mar	Apr	May
Max hourly		61; 10.5; 163.8; (11, 14:00)	62.6; 8.7; 136.3; (10, 14:00)	57.9 7.4; 173.8; (28, 15:00)	27.2; 3.6; 156.3; (28, 14:00)	24.7; 3.9; 157.5; (6, 16:00)
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0;	3.6; 3.4; 20; (23, 15:00)	49.3; 8.6; 3.8; (17, 16:00)	74.2; 10.4; 176.3; (30, 13:00)	92.3; 10.3; 166.3; (2, 16:00)	62.9; 11.4; 183.8; (3, 15:00)	117.2 8.7; 26.3; (21, 13:00)

Table 2. Exfiltration sensible loss rate of L2 - Foyer (infiltration modelling with AFN)

Infiltration sensible loss rate (kW); Wind speed (m/s); Wind direction (deg) (date, time)		Jan	Feb	Mar	Apr	May
Max hourly		76.3; 7.4; 163.8; (18, 7:00)	77.9; 10.3; 180; (27, 7:00)	91.7; 10.5; 186.3; (14, 6:00)	102.6 7.5; 253.8; (22, 7:00)	121.4 8.9; 163.8; (20, 21:00)
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
120.4 4.4; 173.8; (22, 8:00)	79.7; 2.8; 309; (27, 8:00)	83.2 14.4 187.5 (25, 19:00)	130.4; 17.2; 173.8; (7, 8:00)	129.1; 14.6; 170; (8, 15:00)	121; 10.2; 170; (6, 6:00)	119.4; 12.1; 173.8; (12, 6:00)

Table 3. Zone sensible cooling energy consumption for L2 - Foyer (infiltration modelling with AFN)

Zone sensible cooling energy (kWh);		Jan	Feb	Mar	Apr	May
Max hourly Max daily Monthly		59.3 585.1 2367.4	58.6 296.2 3217.1	58.8 281.9 1847.6	27.8 95.1 478.1	25.5 95.7 99.7
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0 0 0.2	3.5 4.9 5.9	49.5 219.6 362.9	75.2 370.5 447.1	90 728.5 3105.6	63.7 373.8 1109.2	112.2 985.1 2759.3

Table 4. Zone sensible heating energy consumption for L2 - Foyer (infiltration modelling with AFN)

Zone sensible heating energy (kWh);		Jan	Feb	Mar	Apr	May
Max hourly Max daily Monthly		75.2 806.3 5698.4	75.2 288.2 3664.3	95.7 493.3 7156.9	108.9 711.8 13413.8	122.8 895.3 15775.2
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
122.5 1121.1 23448.8	75.4 1201.8 25510.6	75.5 1049 22639.6	123 1540.6 20970.7	123.1 1573.5 20412.8	122.2 836.5 13494.9	121.3 357.7 11010.8

Table 5. Zone sensible cooling energy consumption for L2 - Foyer (base model with no AFN)

Zone sensible cooling energy (kWh);		Jan	Feb	Mar	Apr	May
Max hourly Max daily Monthly		2.94 20 361.2	3.3 17.1 328.9	3 17.8 250.3	1.1 7.6 148.2	1.5 10.1 151.9
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0.5 5 119.5	0.6 4 128.5	1.1 10 155.6	2 15.8 246.9	3.3 20.7 246.2	2 10.5 238.4	3.3 32.9 318.9

Table 6. Zone sensible heating energy consumption for L2 - Foyer (base model with no AFN)

Zone sensible heating energy (kWh);		Jan	Feb	Mar	Apr	May
Max hourly Max daily Monthly		2.7 6.4 41.3	1.9 1.9 31.1	2.3 2.4 54	3.1 6.8 108.1	3.1 8.5 82.6
Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
3.6 5.6 154.6	4.4 16.5 223.5	3.3 4.4 156.7	3.2 6.3 62.9	3.4 9.3 108.1	2.6 3.1 65	1.9 1.9 58.1

The annual cooling energy results from the infiltration model show approximately 20,000 kWh/annum more energy used in L2-Foyer. This number is one order of magnitude higher compared to the base model where library L2-Foyer doors were set to closed preventing wind driven infiltration/exfiltration (see Table 7).

Table 7. Annual energy consumption comparison between two scenarios; infiltration modelling with AFN and base case with no AFN

Air Handling Unit	Total Cooling (AFN), kWh	Total Cooling (base), kWh	Total AFN-Total base	Total heating (AFN), kWh	Total heating (base), kWh	Total AFN-Total base
AHU1	49812.1	50092	-279.9	17857.1	13535.6	4321.5
AHU2	266874	273935	-7061.4	32859.3	29798.5	3060.8
AHU3	63643.3	67253.6	-3610.3	2572.2	2584.6	-12.4
AHU4	284299	291854	-7555.6	2548.7	2565.5	-16.8
AHU5	151433	147159	4273.6	91565.2	84263.8	7301.4
AHU6	171066	195279	-24214	3445.4	3547	-101.6
AHU7	111997	114027	-2030.6	0.5	0.5	0
AHU8	44692.5	47391.5	-2699	381.7	255.6	126.1
AHU9	9392.1	10065.3	-673.2	428.7	159.9	268.8
AHU10	19307.8	19747.7	-439.9	1231.4	1142.4	89
AHU11	87398.4	86709.7	688.7	1.3	1.3	0
AHU12	40104.4	40455.5	-351.1	665.6	715.9	-50.3
AHU13	13942.7	14531.6	-588.9	424.2	376.3	47.9
AHU14	22223.1	22759.6	-536.5	601.7	681.4	-79.7
AHU15	14946	15008.8	-62.8	925.5	1037	-111.5
AHU16	249325	244279	5045.9	11533	2082.7	9450.3
AHU17	69335.7	73019.7	-3684	722.2	477.5	244.7
AHU18	53522.8	57674	-4151.2	574.3	457.8	116.5
AHU19	40393.9	40919.5	-525.6	0.9	1	-0.1
AHU20	19643.5	20376.9	-733.4	571.5	573.8	-2.3
AHU21	61729.6	64441.6	-2712	0.4	0.4	0
AHU22	74076.7	76421.1	-2344.4	0	0	0
AHU23	31875.9	32364.1	-488.2	8097.6	7444.5	653.1
AHU24	337405	348525	-11121	6173	7585.8	-1412.8
AHU25	24835.2	22104.3	2730.9	3659.9	490.5	3169.4
AHU26	307029	269424	37605.5	113770	57268.6	56501.1
FCU1	4702.3	4761.6	-59.3	1375.1	1322.9	52.2
FCU2	6740.7	6867.2	-126.5	4739.6	4665.5	74.1
FCU3	6191	6209.4	-18.4	2864.3	2842.7	21.6
FCU4	2348.6	2312.8	35.8	3.4	4.6	-1.2
FCU5	12535.2	12707.9	-172.7	2232.7	2179.1	53.6
FCU6	2207.2	2235.4	-28.2	1762.4	1748.6	13.8
FCU7	3610.4	3904.8	-294.4	3781.4	3156.3	625.1
FCU8	1702.1	1776.8	-74.7	1135.5	721.4	414.1
FCU9	8849.2	7132.8	1716.4	4185.3	1374.8	2810.5
FCU10	3161	3451.9	-290.9	0	0	0
FCU11	1053.7	957.6	96.1	1900.4	758.3	1142.1
FCU12	12711.1	12582.8	128.3	90	85.7	4.3
FCU13	1458.1	1431.3	26.8	837.3	798	39.3
FCU14	22813.2	2042.6	20770.6	369683	3262	366421
FCU15	11050.9	11634.9	-584	14200	8807.8	5392.2
Bldg	2,721,437	2,725,830	-4,392.7	709,402	248,776	460,626

However, other areas in the building particularly internal zones lumped together between floors with large volume interconnected air space such as the atria could benefit from the air movement induced by this infiltration/exfiltration to dissipate some of the heat. This tendency actually works to compensate the extra energy needed to cool L2-Foyer from the infiltration heat gain leading to a saving of approximately 4,400 kWh/annum.

The difference in total heating energy of FCU14 serving L2-Foyer for the two models in Table 7 shows the heat loss through the doors particularly in winter is very significant. The overall heat loss due to exfiltration that has to be made up by providing heating for space conditioning is approximately 460,000 kWh/annum more than the base model, of which approximately 50% comes from wind-driven exfiltration heat loss in L2-Foyer through the three doors.

Also from the comparisons above, the annual energy consumption due to infiltration/exfiltration through the three doors in L2-Foyer makes up approximately 13.3% of the annual building total energy consumption for cooling and heating, when considered from thermal energy on the air/demand side.

CONCLUSIONS

Several concluding remarks to be summarised as follows:

1. The cooling energy consumption of the foyer with doors exposed to outdoor is approximately 20,000 kWh/annum or one order of magnitude higher than the scenario without infiltration modelling where the doors were fixed closed.

2. Other rooms that have interconnected air space as part of the air flow network in the building may actually benefit from the wind driven infiltration/exfiltration air movement to dissipate some of the heat loads resulting in compensating energy savings to a certain extent. But this is typically only a small percentage.

3. The total heating energy of the infiltration model was found to be significantly higher (more than 150%) than the base model of which the bulk (of approximately 50%) comes from wind driven exfiltration heat loss through the doors.

4. Infiltration could make up a significant proportion of energy consumption in large buildings if there are wind-exposed doors/windows without proper amelioration measures.

NOMENCLATURE

Cp = Wind surface pressure coefficient [dimensionless]

g = gravity acceleration [9.81 m/s^2]

p = surface pressure, total pressure [Pa]

P = static pressure, total pressure [Pa]

V = speed [m/s]

z = elevation [m]

ρ = Air density [kg/m3]

subscripts

n, m = nodes; N = entry; M = exit

s = difference due to density and height

w = wind relative to static pressure in undisturbed flow; difference due to wind

ref = reference at local height

Δ = differential

REFERENCES

ASHRAE Handbook 1997. Fundamentals, SI Edition, American Society of Heating, Refrigeration and Air-conditioning Engineers Inc.

EnergyPlus version 3.1 2009. Input Output Reference, US DOE, USA.