VENTILATED BUILDINGS OPTIMISATION BY USING A COUPLED THERMAL-AIRFLOW SIMULATION PROGRAM

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ABSTRACT

This work shows the optimization of natural ventilation within buildings at the stage of design and behaviour of the occupants. An evaluation is done by coupled multizone air modelling and thermal building simulation by using a deterministic set of input factors comprising among others climate, local environment, building characteristics, building systems, behaviour of occupants, heat loads. Selected deterministic input factors were varied to generate additional information applied in an optimization loop.

With that, it is found that the optimal solution depends to a great deal on the possibility of combined optimization of the behaviour of occupants with a lesser extent of the design building.

INTRODUCTION

The energy situation in the world is becoming alarming. The demand for electric power continues to grow whereas the means of production remain limited. A great number of countries that need high sources of power are in the inter-tropical zone and are thus subjected to high temperatures and humidity all year long. These climates and the increase in the purchasing power of the populations lead to greater use of air-conditioning (Bastide *et al, 2006*).

Air-conditioning is often seen as the only mean to reach thermal comfort during the hot season and unfortunately is very energy consumer.

Furthermore, the electric power produced from fossil energies will disappear in the coming decades. Before the disappearance of these resources, galloping inflation, due mainly to the scarcity of these fuels, will make their purchase at reasonable prices impossible. It will then become too expensive to operate these air-conditioning systems (*Ibidem)*.

Afterwards, a way to cool down buildings without using great amounts of energy must be found, otherwise, comfort and health hassles could get started.

For the right environmental conditions, naturally ventilated buildings can be one of the ways to obtain thermal comfort while maintaining low energy consumption of the building (Assiakopoulos *et al, 2002*).

In order to do that, it is necessary to know the behaviour of the ventilation according to its characteristics.

By knowing this behaviour, it is possible to optimize natural ventilation by changing its characteristics, shown like deterministic inputs in this case.

The aim of this work is to show different results of the indoor air temperature in a building by changing different parameters, trying to find which of these parameters are the most important to optimize natural ventilation.

This quest is going to be done by the coupled thermal-airflow building simulation program Energy Plus.

Energy Plus is a coupling of the zone heat balance with the zone airflow balance. The way of coupling of Energy Plus is a coupled iterative approach (onion coupling).

SIMULATION

To simulate, a set of inputs is set. The set is divided by three main groups, these groups are: behaviour of the occupants, building design and outdoor conditions. Each one of them has the following data:

Behaviour of the occupants
- Number of occupants
- Schedule of occupants
- Use of electric devices
- Internal heat sources
- Window openings
- Temperature set point
- Solar shading operation

Building design
- Materials of construction
- Building shape
- Building orientation
- Openings sizes
- Openings orientations
- Openings shapes
- Surroundings
  - Adjacent constructions
  - Adjacent trees
  - Adjacent heat/cold sources
  - Adjacent moisture sources
- HVAC systems

- o Air-conditioning
- o Heating systems
- o Heat exchangers
- o Fans
- o Radiant floor
- o Green roofs
- o Heat pumps

Outdoor conditions
- Outdoor temperature
- Relative humidity
- Wind speed
- Wind direction

Theoretical reference

The coupling in Energy Plus starts with a heat balance on the zone air:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \tag{1}$$

$$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys}$$

An analytical solution algorithm provides a possible way to obtain solutions without truncation errors and independent of time step length. In addition, the algorithm only requires the indoor air temperature for one previous time step, instead of three previous time steps as required by the 3rd order backward difference. The analytical solution for equation (1) may be expressed as follows:

$$T_z^t = \left(T_z^{t-\delta t} - \frac{\sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_\infty + \dot{m}_{sys} C_p T_{sup}}{\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p} \right)$$

$$* \exp\left(- \frac{\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p}{C_z} \delta t \right)$$

$$+ \frac{\sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_\infty + \dot{m}_{sys} C_p T_{sup}}{\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p}$$

$$\tag{2}$$

Equation (2) shows the solution of the heat balance in the zone air for the indoor air temperature. Therefore, the flow rate due to infiltration, $\dot{m}_{inf}$, and natural ventilation, $\dot{m}_{sys}$, (if the zone is totally naturally ventilated), could be found by the Effective Leakage Area model which is based on Sherman and Grimsrud (1980). The model formulation used in Energy Plus is from the ASHRAE Handbook of Fundamentals (2001 and 2005). The model is:

$$V_{inf} = (F_{Schedule}) \frac{A_L}{1000} \sqrt{C_s |T_\infty - T_z| + C_w (s_{wind})^2} \tag{3}$$

The ventilation airflow rate is a function of the wind speed and the thermal stack effect (actually, is a function of mechanical driving forces as well, but in this case a complete naturally ventilated building is considered).

In Energy Plus, the natural ventilation flow rate can be controlled by a multiplier fraction schedule applied to the user-defined opening area and through the specification of minimum, maximum and delta temperatures. The equation used to calculate the ventilation rate driven by wind is the following

$$\dot{V}_{wind} = O_w A_{opening} F_{schedule} s_{wind} \tag{4}$$

The opening effectiveness is calculated for each time step based on the angle between the actual wind direction and the effective angle of the wind entrance using the following equation:

$$O_w = 0.55 + \frac{|\alpha_{effective} - \alpha_{wind}|}{180} \cdot 0.25 \tag{5}$$

The difference between the effective angle and the wind direction should be between 0 and 180 degrees. This equation is a linear interpolation using the values recommended by the 2009 ASHRAE Handbook of Fundamentals: 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonals winds.

The equation used for calculating the ventilation rate due to stack effect is given by equation (6)

$$V_{stack} = C_D A_{opening} F_{Schedule} \sqrt{2 g \Delta H_{NPL} \frac{(|T_z - T_\infty|)}{T_{zone}}} \tag{6}$$

The discharge coefficient for opening is given by the following equation:

$$C_D = 0.40 + 0.0045 |T_z - T_\infty| \tag{7}$$

The total ventilation rate calculated by this model is the quadratic sum of the wind and stack air flow components:

$$V_{wind-stack} = \sqrt{(V_{satck})^2 + (\dot{V}_{wind})^2} \tag{8}$$

So, $\dot{m}_{inf}$ and $\dot{m}_{sys}$, could be calculated by the followings equations

$$\dot{m}_{\text{inf}} = \dot{V}_{\text{inf}} \cdot \rho_c \qquad (9)$$

$$\dot{m}_{sys} = \dot{V}_{wind-stack} \cdot \rho_c \qquad (10)$$

Furthermore, the temperature of comfort is given by Auliciems (1981) as follows

$$T_{be} = (17.6 + 0.31T_m) \pm 2.5 \quad (11)$$

The optimization of one specific case in a warm region is presented in this work. The building is a construction of 10.8 m of length, 10.8 m of width and 3 m of height. It has two zones of the same size, each one has two windows.
The schedule of working of the building is a typically office schedule in Mexico: from 7:00 until 19:00 hrs.
The building is located in Mexico City; the material of construction is concrete.
The day of analysis is March the 1st. According to a previous study, the month of March represents the best sample of weather data in Mexico, where the outdoor conditions are very similar all year long.
The characteristics of the building are the following:

Table 1
Characteristics of the building

BEHAVIOUR OF THE OCCUPANTS	
Number of occupants	20 people, 5 at zone one and 15 at zone two
Schedule of occupants	Office schedule (7 am to 7 pm)
Use of electric devices	4000 W in total, 1000 zone one and 3000 zone two
Gas equipment	1000 W
Window opening	According to the schedule and the temperature setpoint
BUILDING DESIGN	
Building design	Construction of one floor, with two zones
Building dimension	Length 10.8 m, width 10.8 m, height 3 m
Materials of construction	Brick in the walls, concrete in the roof and floor
Opening size	6 m^2 each window
Openings shape	4 m length, 1.5 m height each one
Openings orientation	South and west (zone one); north and east (zone two)
Interzone path material	Oak
Interzone path size	Door of 3.08 m^2
Surroundings	No
HVAC systems	No
OUTDOOR CONDITIONS	
Outdoor temperature	According to the historical weather conditions
Wind speed	0.5, 2.0, 3.5, 5.0 m/s
Wind direction	45° (North=0°, south=180°)

The window opening activity is according to the schedule and the temperature setpoint, which means that the openings are open or closed depending on the

schedule of the building and/or the comfort temperature setpoint that is given by T_{be} from equation (11).
The gas equipment is a boiler that heat up water used in the restrooms area.
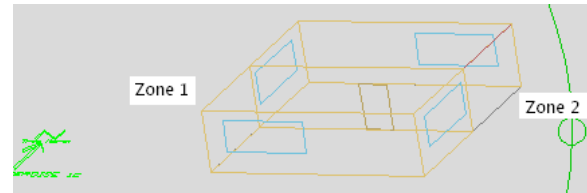The geometry and shape of the building is shown in Figure 1:

Figure 1 Building geometry

Several simulations were done for getting the lowest indoor air temperature, especially from 10 am to 8 pm. Finally, it was found that air velocity, openings activity and shape of the openings were the most important variables to change.

DISCUSSION AND RESULTS ANALYSIS

A comparison between outdoor air temperature and indoor air temperature in building at different outdoor air velocities is shown in Figure 2.
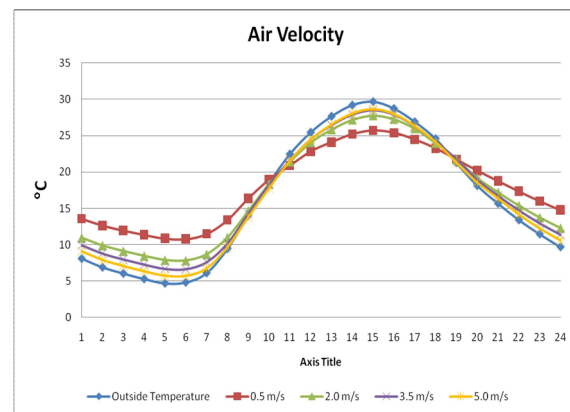

Figure 2 Indoor air temperature with different outdoor air velocities

It can see that from 22:00 to 4:00 hrs of the next day is when there is the highest difference between the different indoor air temperatures. And during the office schedule, the difference between these temperatures is minimal. From 10:00 to 19:00 all indoor air temperatures are below of the outdoor air temperature.
Figure 3 shows the indoor air temperature by setting three different sizes of the openings (4 m x 1.5 m, 2 m x 1.5 m, 2 m x 2 m). The air velocity is 2 m/s in all cases and the wind direction is 45°.
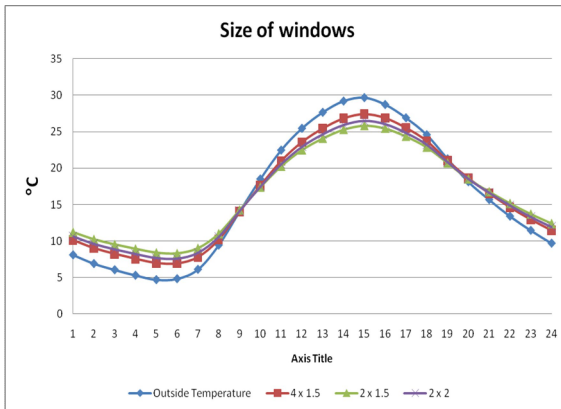
Figure 3 Indoor air temperature

If the openings are closed in their totality, there is an almost-constant temperature all day long. The sizes of the windows are 4 m x 1.5 m and the air velocity is 2 m/s. The results are shown in the figure 4 as follows.
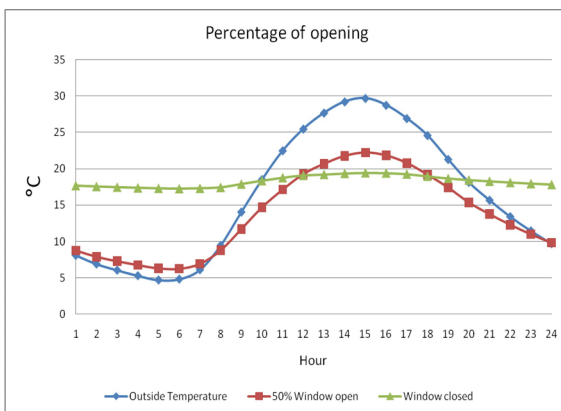

Figure 4 Indoor air temperature with closed windows and half-open windows

According to the three graphs above, only when the percentage of openings is changed there is an important difference between the indoor air temperatures.

The best air velocity to cold down the building during high outdoor temperature is 0.5 m/s (figure 1). The size of windows to keep cool the building is 2 m x 1.5 m (figure 2).

According to figure 3, a 50% of windows open helps to reduce the indoor air temperature.

Thus, and taking into account others characteristics of the building design and the behaviour of the users, it was found that the windows opening activity represents the most important factor to the indoor air temperature, which is up to a point logical.

Therefore, in the case when the windows are kept closed, and the power of the gas equipment to heat water is increased, indoor air temperature increases less than one Celsius degree for each 1000 W more

of power. The results can be watched in the following figure.
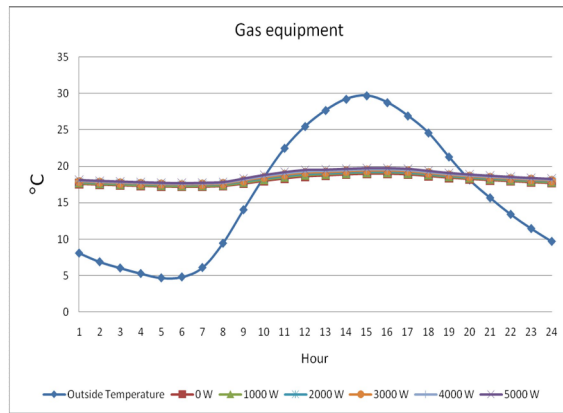

Figure 5 Indoor air temperature with closed windows and different power of gas equipment

In the results shown above, it seem that even when there is a high outdoor air velocity, when the size of the openings is different, or when the power of the gas equipment is increased, the temperature does not vary more than a few Celsius degrees. In Energy Plus, the schedule factor, $F_{Schedule}$, presented in equations (3), (4) and (6) is a dimensionless value between 0 and 1 that is controlled by among others the temperature setpoint given by the user. In the case, $F_{Schedule}$ has a value of 0.25. That means that the windows are opened a quarter of their area and depending of the schedule of the user, an office schedule (from 7 am to 7 pm) is in this simulation. Also, in this case, the temperature setpoint has a value between the lowest and the highest outdoor temperature. In the case when the indoor air temperature was higher than the outdoor temperature the windows will open more.

Thus, to optimise the natural ventilation during warm seasons is necessary to minimize equation (2) in order to get the lowest T_z^t and to get the comfort temperature given by equation (11). For doing that, and like was analysed in the results from the simulations, the most important term is $F_{Schedule}$, presented in equations (3), (4) and (6) that give the volume flow rate due to infiltration, driving wind and stack effect, respectively.

CONCLUSION

Energy Plus is a program that uses an approach in which the thermal and airflow model iterate within one time step until satisfactory small error estimates are achieved.

Energy Plus, in order to control the openings, uses a multiplier fraction schedule applied to the user-defined opening area and through the specification of minimum, maximum and delta temperatures.

Even when there are several characteristics of the design building and the behaviour of the occupants

that could be changed to get the optimal efficiency of natural ventilation, the variable which has the biggest influence is the opening of windows by the users of the building.

Nevertheless, it was found that in many cases keeping the windows opened is not an assurance for getting thermal comfort in the buildings. It is necessary to analyse each building with its own characteristics of design, behaviour of the users and outdoor conditions, as well as its own needs of comfort.

However, it should be noted that these simulations did not include characteristics from the set of inputs which could be important in the work, but they will take into account for future studies.

Furthermore, is very important to say that this work was done by using deterministic inputs, but for getting more realistic results, stochastic modelling is necessary. Thus, the next purpose of the work is to keep simulating with an optimization of naturally ventilated building by using random data.

NOMENCLATURE

$\alpha_{effective}$ = Effective angle of the wind entrance [º]

α_{wind} = Wind direction [º]

ρ_c = Density of the air at sea level and 20ºC $\left[1.2 kg/m^3\right]$

ΔH_{NPL} = Height from midpoint of lower opening to the Neutral Pressure Level $[m]$

$A_{opening}$ = Opening area $\left[m^2\right]$

A_i = Area of the zone surface i $\left[m^2\right]$

A_L = Effective air leakage area in cm^2 that corresponds to a 4 Pa pressure differential

C_D = Discharge coefficient for opening [*dimensionless*]

C_p = Specific heat of the air $\left[J/kgK\right]$

C_s = Coefficient for stack-induced infiltration $\left[(L/s)^2/cm^4 K\right]$

C_w = Coefficient for wind-induced infiltration $\left[(L/s)^2/cm^4 (m/s)^2\right]$

C_z = Air capacitance $\left[J/K\right]$

$F_{schedule}$ = Value from a user-defined schedule $[0..1]$

h_i = Heat transfer coefficient $\left[W/m^2 K\right]$

m_{inf} = Mass air flow due to infiltration $\left[kg/s\right]$

$\dot{m}_i$ = Mass air flow due to interzone air mixing $\left[kg/s\right]$

$\dot{m}_{sys}$ = Mass air flow of the systems $\left[kg/s\right]$

O_w = Opening effectiveness [*dimensionless*]

$\dot{Q}_i$ = Convective internal loads $\left[J/s\right]$

$\dot{Q}_{sys}$ = Energy of the air systems $\left[W\right]$

s_{wind} = Local wind speed $\left[m/s\right]$

t = Time $[s]$

T_{be} = New base reference temperature $[K]$

T_m = Mean annual temperature $[K]$

T_z = Indoor air temperature $[K]$

T_z^t = Indoor air temperature at the time step t $[K]$

$T_z^{t-\delta t}$ = Indoor air temperature at the previous time step t $[K]$

T_{zi} = Temperature in zone i $[K]$

T_{si} = Temperature in surface i $[K]$

T_∞ = Outdoor air temperature $[K]$

T_{sup} = Temperature of the supply air $[K]$

$\dot{V}_{stack}$ = Volume flow rate due stack effect $\left[m^3/s\right]$

$\dot{V}_{wind}$ = Volume flow rate driven by wind $\left[m^3/s\right]$

$\dot{V}_{stack-wind}$ = Volume natural ventilation rate $\left[m^3/s\right]$

$\sum_{i=1}^{N_{sl}} Q_i$ = Sum of the convective internal loads $\left[J/s\right]$

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$ = Convective heat transfer from the zone surfaces $\left[J/s\right]$

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = Heat transfer due to interzone air mixing $\left[J/s\right]$

$\dot{m}_{inf} C_p (T_\infty - T_z)$ = Heat transfer due to infiltration of outsider air $\left[J/s\right]$

$\dot{Q}_{sys}$ = Air Systems output $\left[J/s\right]$

$C_z \dfrac{dT_z}{dt}$ = Energy stored in the zone air $\left[J/s\right]$

REFERENCES

Auliciems, A., 1981. Towards a psycho-physiological model of thermal perception. Int. J. of Biometeorology 26.

ASHRAE Handbook of Fundamentals. 2001. Chapter 26

ASHRAE Handbook of Fundamentals. 2005. Chapter 27

ASHRAE Handbook of Fundamentals. 2009. Chapter 16

Assiakopoulos, M., Tsangrassoulis, A., Mihalakakou, G., Santamouris, M., Sergé, J. 2002 Development of a control algorithm to optimize airflow rates through variable size windows. Energy and Buildings 34 363–368.

Bastide, A., Lauret, P., Garde, F., Boyer, H. 2006 Building energy efficiency and thermal comfort in tropical climates. Presentation of a numerical approach for predicting the percentage of well-ventilated living spaces in buildings using natural ventilation. Energy and Buildings Volume 38 Pages 1093–1103.

Bjørn, E., Brohus, H. 2006. Overall evaluation of indoor climate and energy for alternative office designs using the eco-factor. Journal of civil engineering and management. Vol. XII, No. 1, 43-49.

Cai, W., Wen, X. 2009. Optimization of natural ventilation system for an exhibition hall. Proceedings of the 2nd International Conference on Modelling and Simulation, ICMS2009 Volume 5 Pages 254-257.

Coblenz, C. W. and Achenbach, P. R. 1963. Field Measurement of Ten Electrically-Heated Houses. ASHRAE Transactions pp 358-365.

Hensen, J. 2000. Modelling coupled heat and air flow: ping-pong vs onions. University of Strathclyde. Energy Systems Research Unit.

Malkawi, A., Augenbroe, G. 2003. Advanced building simulation. Spon Press. ISBN 0-203-07367-3.

Meng, Q., Li, Q., Zhao, L 2007. Evaluation and optimization on indoor wind environment of high-rise residential buildings. Journal of Harbin Institute of Technology Volume 14 Pages 278-281

Sherman, M.H. and D.T. Grimsrud. 1980. Infiltration-pressurization correlation: Simplified physical modeling. ASHRAE Transactions 86(2):778

Spindler, H., Norford, L. 2009 Naturally ventilated and mixed-mode buildings. Part II: Optimal control. Building and Environment Volume 44 Pages 750–761.

Stephan, L., Bastide, A., Wurtz, E. 2011. Optimizing opening dimensions for naturally ventilated buildings. Applied Energy Volume 88 Pages 2791–2801.

Taylor, R. D., C.O. Pedersen, L.K. Lawrie. 1990. Simultaneous Simulation of Buildings and Mechanical Systems in Heat Balance Based Energy Analysis Programs, Proceedings of the 3rd International Conference on System Simulation in Buildings, Liege, Belgium, December 3-5, 1990.

Taylor, R.D., C.O. Pedersen, D.E. Fisher, R. J. Liesen, L.K. Lawrie. 1991. Impact of Simultaneous Simulation of Buildings and Mechanical Systems in Heat Balance Based Energy Analysis Programs on System Response and Control, Conference Proceedings IBPSA Building Simulation '91, Nice, France, August 20-22, 1991.

Walker, I.S., and D.J. Wilson. 1998. Field validation of equations for stack and wind driven airinfiltration calculations. International Journal of HVAC&R Research 4(2).