Natural Ventilation: A Mitigation Strategy to Reduce Overheating In Buildings under Urban Heat Island Effect in South American Cities

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Abstract. Urban heat island effect often produces an increase of overheating sensation inside of buildings. To evacuate this heat, the current use of air conditioning increases the energy consumption of buildings. As a good alternative, natural ventilation is one of the best strategies to obtain indoor comfort conditions, even in summer season, if buildings and urban designs are appropriated. In this work, the overheating risk of a small house is evaluated in four South American cities: Guayaquil, Lima, Antofagasta and Valparaíso, with and without considering the UHI effect. Then, natural ventilation is assessed in order to understand the capability of this passive strategy to assure comfort inside the house. Results show that an important portion of the indoor heat can be evacuated, however the temperature rising (especially during the night) due to UHI can generate a saturation effect if appropriate technical solutions, like the increase in the air speed that can be obtained with good urban design, are not considered.

1. Introduction

Natural ventilation is a common strategy to avoid overheating in buildings, especially residential, in many South American countries. However, two major phenomenon might threat the current urban situation in the continent: 1) the general temperatures increase due to Climate Change (CC) and; 2) the urban heat island (UHI) effect generated by intensive urbanization which is dramatic in this region of the world [1,2]. This situation could generate a massive increase in the use of air conditioning systems, even where those kinds of appliances have been absent for cultural and climatic reasons. To cope with this new methodologies and approached are needed, especially looking at the inclusion of innovative measures in buildings and urban design norms. In this work, an evaluation of the current overheating risk in small houses in four important cities in South America was done: Guayaquil, Lima, Antofagasta and Valparaíso. To account for the UHI effect, the analysis was performed considering and not considering the UHI in the simulation. Then, an estimation of the natural ventilation power to evacuate this heat is done in both conditions, with and without UHI. Natural ventilation is studied considering the wind as the driving force, two cases are separately analyzed: 24-hours cross ventilation and nocturnal cross ventilation.
2. Methodology

In this paper, an overheating assessment of a small house is done first, using meteorological data from ASHRAE [3] to estimate temperature and solar radiation. Radiation on the exposed surfaces (North, South, East and West) is calculated by using TRNSYS Studio v. 17 © [4]. Then, a simplified method is used to assess the natural ventilation potential for the house in different supposition of orientation and internal distribution. Both overheating and natural ventilation calculations are done for the rural case and the urban case. Hourly urban temperatures were obtained by Urban Weather Generator © [5] simulation tool for a 90 days period. The average diurnal and nocturnal temperatures are used in the method.

2.1. Overheating risk for residential buildings calculation

Overheating risk is calculated by using a method based on the EN ISO 13790 [6], which considers average daily temperatures and a correction to take into account the heat accumulation in the thermal mass. The UHI effect was estimated by changing the average temperature on simulations done with the Urban Weather Generation © tool. To estimate the overheating, many factors were considered. The following set of equations resume the quantitative method. First term to be considered is:

\[ SGO = R \times S \times \alpha \times R_{es} \times U \]  \hspace{1cm} (1)

where:
- \( SGO \) is the solar gain through the opaque envelope elements (J)
- \( R \) is the incoming solar radiation (J/m²)
- \( S \) is the surface of the opaque element (m²)
- \( \alpha \) is the solar absorption of the surface
- \( R_{es} \) is the external surface thermal resistance (m²K/W)
- \( U \) is the transmittance of the element (W/Km²)

The second term is:

\[ SGW = R \times S \times f_f \times f_{sg} \times f_{mp} \times f_a \]  \hspace{1cm} (2)

where:
- \( SGW \) is the solar gain through the windows (J)
- \( R \) is the incoming solar radiation (J/m²)
- \( S \) is the surface of the element (m²)
- \( f_f \) is the framework coefficient of the window
- \( f_{sg} \) is the solar factor of the glass
- \( f_{mp} \) is the factor of mobile protection of the window
- \( f_a \) is the accessibility factor due to external shadows

The third term to be considered is:

\[ IG = \sum P \times S \times t \]  \hspace{1cm} (3)

where:
- \( IG \) is the internal heat gain (J)
- \( P \) is the heat generated by each appliance and by people (W)
- \( S \) is the floor surface of the zone (m²)
- \( t \) is the time of functioning or occupation (s)
The total gain is expressed by:

\[ TG = IG + \sum SGO + \sum SGW \]  \hspace{1cm} (4)

Part of this heat is evacuated by thermal transmission through the envelope and the other part represents the overheating OH:

\[ OH = TG - (T - T_A) \times H_t \times \eta \]  \hspace{1cm} (5)

where
- \( T_A \) is the daily average temperature (°C)
- \( T \) is the internal temperature (set as adaptive comfort temperature)
- \( H_t \) is the thermal loss (J/°C) by transmission through the envelope
- \( \eta \) is the efficiency of the heat loss and depends on the thermal capacitance of the building’s mass

Adaptive comfort concept refers to the maximum temperature that people living in free-running buildings would accept as comfortable. This temperature depends on the external temperature and has been expressed by different experimental formulas \[7\], \[8\]. In this paper the expression used is:

\[ T = \max(0.35 T_A + 17.8; 26) \]  \hspace{1cm} (6)

This means that comfort temperature is set to 26 degrees Celsius (Antofagasta and Lima) or the adaptive comfort temperature in function of the external daily average temperature (Guayaquil and Valparaiso).

Meteorological data used in calculation were obtained by ASHRAE (temperatures) and by using epw files (solar radiation) produced by Meteonorm © [9] tool and processed by using TRNSYS 17 © in order to obtain the radiation on the vertical surfaces. Table 1 resumes the data.

| Table 1: meteorological data used (total radiation and average temperature of the period) |
|----------------------------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|-----------------|
| Horizontal (MJ/m²) | North (MJ/m²) | South (MJ/m²) | East (MJ/m²) | West (MJ/m²) | Ta night (°C) | Ta 24h (°C) | Ta UHI night | Ta UHI 24h |
| Lima | 1,840 | 670 | 695 | 910 | 910 | 19.2 | 21.8 | 19.4 | 21.9 |
| Guayaquil | 1,610 | 581 | 772 | 885 | 949 | 24.5 | 27.5 | 26.1 | 28.1 |
| Antofagasta | 2,160 | 817 | 625 | 1,240 | 1,170 | 17.5 | 20.1 | 18.0 | 20.6 |
| Valparaiso | 1,880 | 882 | 629 | 1,170 | 1,040 | 17.8 | 21.5 | 22.7 | 23.2 |

2.2. Natural ventilation potential calculation

Natural ventilation potential is estimated by using a simplified method, also following EN ISO 13790, and considering separately the case of 24-hours and nocturnal ventilation. In the case of nocturnal ventilation, the average temperature between 8 and 20 is considered as air temperature, whilst in the case of diurnal ventilation the average daily temperature is used.

To evaluate the natural ventilation capacity to evacuate heat, the following equation was used:

\[ NVH = (T - T_v) \times (H_v) \times \eta \]  \hspace{1cm} (7)

where:
• \( NVH \) is the heat removed by natural ventilation (J)
• \( T_p \) is the air temperature (daily average or 8-20 average depending on the case) (°C)
• \( H_p \) is the thermal loss (J/°C) by ventilation
• \( \eta \) is the efficiency of the heat loss

The thermal loss by ventilation is expressed as:

\[
H_p = t \times \delta \times sh \times q
\]  

(8)

where:
• \( t \) is the period (s)
• \( \delta \) is the density of the air (kg/m³)
• \( sh \) is the specific heat of the air (J/kgK)
• \( q \) is the flow (m³/s)

The airflow has to be assessed by analyzing the geometric characters of the house and the windows typologies and depends on few parameters: two discharge coefficients \( c_{d,i} \) and \( c_{d,o} \) (inlet and outlet of the air), two pressure coefficients \( c_{p,i} \) and \( c_{p,o} \) (on the façades where the windows are placed) and one internal coefficient \( c_i \) (depending on the space distribution and connection).

The final formula is:

\[
q = v \times \sqrt{\frac{\left| c_{p,i} - c_{p,o} \right|}{c_{d,i} \times s_1 + c_{d,o} \times s_2}}
\]  

(9)

Where \( s \) are the surface of inlet, distribution and outlet respectively.

Final heat to be removed (FRH) can be expressed as:

\[
FRH = OH - NVH
\]  

(10)

By comparing the overheating \( OH \) and the final heat to be removed FRH the effectiveness of the natural cross-ventilation can be obtained.

Two house orientations respect to the main wind and two internal distributions were tested in this work. Figure 1 shows the well-connected and the poorly connected space distribution of the analyzed houses. Table 2 shows the houses and windows dimensions. The house has only two windows, on each of the main façades. Pressure coefficients depend on the relationship height/width and length/width of the house. Table 3 resumes the coefficients used and the air flows calculations for the two considered orientations. Air speed used was 1 m/s. Details for coefficient calculation are described in references [10], [11], [12].

| Table 2: dimensions of the house and windows |
|--------------------------------------------|
| H (m) | L (m) | W (m) | S (m²) | H/W | L/W |
|-------|-------|-------|--------|------|------|
| House | 3.5   | 10    | 7      | 70   | 0.5  | 1.43 |
| Windows | 1   | 1     | na     | 1    | na   | na   |
Figure 1: two houses, representative of a well-connected and of a poorly connected distribution.

Table 3: wind coefficients and flow through the house

|          | Cpi | Cpo | Cdi | Cdo | Ci (wc) | Q (wc) | Ci (pc) | Q (pc) |
|----------|-----|-----|-----|-----|---------|--------|---------|--------|
| House 45°| 0.10| -0.35| 0.70| 1.00| 0.80    | 0.31 m³/s | 0.30 | 0.18 m³/s |
| House 90°| 0.70| -0.20| 0.70| 1.00| 0.80    | 0.44 m³/s | 0.30 | 0.25 m³/s |

3. Results and discussions
Urban heat island intensity for a summer week in the four considered cities is shown in figures 2 to 5. Different urban scenarios are shown, obtained according to methodology developed by Palme et al. [13], [14]. Valparaiso and Guayaquil have higher UHI intensities (up to 10 °C during some nights in the case of Valparaiso).

Figure 2: UHI intensity in Guayaquil during a summer week
Figure 3: UHI intensity in Lima during a summer week

Figure 4: UHI intensity in Antofagasta during a summer week

Figure 5: UHI intensity in Valparaíso during a summer week
Table 4: overheating, residual heat and energy saving for rural and urban case

|                      | Overheating | Heat to be removed | Energy saving | Overheating UHI | Heat to be removed UHI | Saving UHI |
|----------------------|-------------|--------------------|---------------|-----------------|------------------------|------------|
| **24-HOURS VENTILATION** |             |                    |               |                 |                        |            |
| **LIMA**             |             |                    |               |                 |                        |            |
| House 90° (wc)       | 9,186 MJ    | 297 MJ             | 96 %          | 9,454 MJ        | 351 MJ                 | 95 %       |
| House 90° (pc)       | 9,186 MJ    | 1,677 MJ           | 82 %          | 9,454 MJ        | 1,892 MJ               | 80 %       |
| House 45° (wc)       | 9,186 MJ    | 966 MJ             | 89 %          | 9,454 MJ        | 1,111 MJ               | 88 %       |
| House 45° (pc)       | 9,186 MJ    | 3,144 MJ           | 66 %          | 9,454 MJ        | 3,441 MJ               | 63 %       |
| **GUAYAQUIL**        |             |                    |               |                 |                        |            |
| House 90° (wc)       | 17,451 MJ   | 13,428 MJ          | 23 %          | 19447 MJ        | 18,477 MJ              | 5 %        |
| House 90° (pc)       | 17,451 MJ   | 15,157 MJ          | 13 %          | 19447 MJ        | 18,893 MJ              | 3 %        |
| House 45° (wc)       | 17,451 MJ   | 14,606 MJ          | 16 %          | 19447 MJ        | 18,761 MJ              | 4 %        |
| House 45° (pc)       | 17,451 MJ   | 15,829 MJ          | 9 %           | 19447 MJ        | 19,055 MJ              | 2 %        |
| **ANTOFAGASTA**      |             |                    |               |                 |                        |            |
| House 90° (wc)       | 5,954 MJ    | 37 MJ              | 99 %          | 7,226 MJ        | 75 MJ                  | 99 %       |
| House 90° (pc)       | 5,954 MJ    | 301 MJ             | 95 %          | 7,226 MJ        | 562 MJ                 | 92 %       |
| House 45° (wc)       | 5,954 MJ    | 147 MJ             | 97 %          | 7,226 MJ        | 284 MJ                 | 96 %       |
| House 45° (pc)       | 5,954 MJ    | 768 MJ             | 87 %          | 7,226 MJ        | 1,322 MJ               | 82 %       |
| **VALPARAISO**       |             |                    |               |                 |                        |            |
| House 90° (wc)       | 7,325 MJ    | 85 MJ              | 99 %          | 13,323 MJ       | 2,823 MJ               | 79 %       |
| House 90° (pc)       | 7,325 MJ    | 626 MJ             | 91 %          | 13,323 MJ       | 6,677 MJ               | 50 %       |
| House 45° (wc)       | 7,325 MJ    | 320 MJ             | 96 %          | 13,323 MJ       | 5,254 MJ               | 60 %       |
| House 45° (pc)       | 7,325 MJ    | 1,444 MJ           | 80 %          | 13,323 MJ       | 8,562 MJ               | 35 %       |
| **NOCTURNAL VENTILATION** |         |                    |               |                 |                        |            |
| **LIMA**             |             |                    |               |                 |                        |            |
| House 90° (wc)       | 9,186 MJ    | 2,491 MJ           | 73 %          | 9,454 MJ        | 2,593 MJ               | 72 %       |
| House 90° (pc)       | 9,186 MJ    | 3,251 MJ           | 65 %          | 9,454 MJ        | 3,486 MJ               | 63 %       |
| House 45° (wc)       | 9,186 MJ    | 2,788 MJ           | 70 %          | 9,454 MJ        | 2,964 MJ               | 69 %       |
| House 45° (pc)       | 9,186 MJ    | 4,332 MJ           | 53 %          | 9,454 MJ        | 4,637 MJ               | 51 %       |
| **GUAYAQUIL**        |             |                    |               |                 |                        |            |
| House 90° (wc)       | 17,451 MJ   | 9,251 MJ           | 47 %          | 19447 MJ        | 14,836 MJ              | 24 %       |
| House 90° (pc)       | 17,451 MJ   | 12,774 MJ          | 27 %          | 19447 MJ        | 16,817 MJ              | 13 %       |
| House 45° (wc)       | 17,451 MJ   | 11,652 MJ          | 33 %          | 19447 MJ        | 16,186 MJ              | 17 %       |
| House 45° (pc)       | 17,451 MJ   | 14,144 MJ          | 19 %          | 19447 MJ        | 17,587 MJ              | 10 %       |
| **ANTOFAGASTA**      |             |                    |               |                 |                        |            |
| House 90° (wc)       | 5,954 MJ    | 3,603 MJ           | 39 %          | 7,226 MJ        | 3,359 MJ               | 53 %       |
| House 90° (pc)       | 5,954 MJ    | 3,016 MJ           | 49 %          | 7,226 MJ        | 3,035 MJ               | 58 %       |
| House 45° (wc)       | 5,954 MJ    | 3,196 MJ           | 46 %          | 7,226 MJ        | 3,079 MJ               | 57 %       |
| House 45° (pc)       | 5,954 MJ    | 2,942 MJ           | 50 %          | 7,226 MJ        | 3,275 MJ               | 55 %       |
| **VALPARAISO**       |             |                    |               |                 |                        |            |
| House 90° (wc)       | 7,325 MJ    | 1,847 MJ           | 75 %          | 13323 MJ        | 7,282 MJ               | 45 %       |
| House 90° (pc)       | 7,325 MJ    | 1,948 MJ           | 74 %          | 13323 MJ        | 9,394 MJ               | 29 %       |
| House 45° (wc)       | 7,325 MJ    | 1,817 MJ           | 75 %          | 13323 MJ        | 8,583 MJ               | 36 %       |
| House 45° (pc)       | 7,325 MJ    | 2,483 MJ           | 66 %          | 13323 MJ        | 10,495 MJ              | 21 %       |
The results clearly show that ventilation is a very good strategy to evacuate heat in the cases of Lima, Antofagasta and Valparaíso, where between 80-100% of the heat evacuation can be achieved in most of the studied conditions. In the case of Guayaquil, nocturnal ventilation is more effective than 24-hours ventilation, between 20-50% versus 10-20%. This is due to the higher air temperature of the emplacement. It has to be noticed that in this work only the sensible heat evacuation by temperature difference is evaluated, without considering the latent heat evacuation. Moreover, no speculation about comfort sensation felt by users is done due to the air speed.

Second consideration is that UHI reduces the natural ventilation capacity to evacuate heat. Higher temperatures traduces in less capacity to absorb sensible heat. It has to be noticed that in this work air temperature is set equal to ambient temperature. This is not an absolute true, because in some cases the breezes are coming from the Sea, with lower temperature than the land environment. Moreover, some research indicates that UHI could actually increase the breeze intensity, due to higher difference between Sea and land temperatures.

Guayaquil and Valparaíso are the most affected environments by the natural ventilation reduction. In Guayaquil nocturnal heat evacuation capacity is turning 10-20%, versus 20-50% without UHI. In Valparaíso, 24-hours heat evacuation capacity is reduced to 35-80%, versus 80-100% without UHI. The case of Antofagasta is different: diurnal capacity decreases but nocturnal capacity increase, due to new balance between conduction and ventilation losses, resulting in a comparable scenario of 80-100% heat evacuation.

In the case of Lima, the change is less important than in the other studied cities. However, the city size should generate many local effects that are not detected by this analysis and are worth of further investigation. In some neighbours, the UHI will probably be a small effect, while in others the UHI will drastically change the thermal stress of the buildings. Some studies show that the city has maximum temperature difference of more than 10 degrees [15].

4. Conclusions

This work presented simplified calculation of the natural cross-ventilation potential to evacuate heat in four important South American cities: Guayaquil, Lima, Antofagasta and Valparaíso. Results confirmed the initial hypothesis that natural ventilation is today a very useful strategy to reach passive cooling of buildings, especially for residential buildings. However, UHI effect will reduce the capability of natural cross ventilation to evacuate heat. This reduction should be in the order of 20-30% in the cases of Valparaíso and Guayaquil, whilst Antofagasta and Lima present a lower reduction. The loss of capability of this passive strategy should be compensate by better design of both buildings and urban environments, in order to avoid the need for air-conditioning and associated energy consumption and greenhouse gases emissions. In the light of our results, better design means principally: 1) a better consideration of the dimension and orientation of windows and solar protections, in order to minimize the solar gains and maximize the air inlet; 2) a better consideration of the dimension and orientation of buildings, in order to increase the cross ventilation within the urban fabric; 3) to restrict the height of buildings in the first coast lines, where the breezes coming from the sea are more generated and can enter the urban tissue. For to accomplish these objectives new standards have to be developed for a better energy performance of the building sector in South-America. Current standards are done considering heat saving but not including heat evacuation, while recent research puts in evidence that UHI and overheating will be a serious urban problem in the XXI Century [16], [17], [18], [19], [20].

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References

[1] Inostroza, L., Baur, R. and Csaplovics, E., 2013. Urban sprawl and fragmentation in Latin America: A dynamic quantification and characterization of spatial patterns. *Journal of environmental management, 115*, pp.87-97.

[2] Inostroza L., 2016. “Climate change adaptation responses in Latin American urban areas. Challenges for Santiago de Chile and Lima”. In “Cambio climatico: lecciones de y para ciudades de America latina”, Nail Ed., Universidad Externado de Colombia, pp. 391-420, ISBN 978-958-772-479-0.

[3] ASHRAE. Weather Data Files CDROM.

[4] W. A. Beckman, L. Broman, A. Fiksel, S. A. Klein, E. Lindberg, M. Schuler, and J. Thornton, “TRNSYS The most complete solar energy system modeling and simulation software,” Renew. Energy, vol. 5, no. 1–4, pp. 486–488, 1994.

[5] B. Bueno, L. Norford, J. Hidalgo, and G. Pigeon, “The urban weather generator,” J. Build. Perform. Simul., vol. 6, pp. 269–281, 2013.

[6] ISO 13790/2008 (rev. 2012) Energy performance of buildings - Calculation of energy use for space heating and cooling.

[7] de Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104(1), 145-167.

[8] de Dear, R., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings, 34, 549-561.

[9] Meteonorm. Available online: www.meteonorm.com (accessed on March 2017).

[10] Palme, M., Carrasco, C., Galvez, M. A. Assessment of The Overheating Risk and the Cooling Power by Natural Ventilation Of Family Houses In Coastal Cities Of Chile. Habitat Sustentable

[11] Heisleberg, Per, Sandberg, Mats. Evaluation of Discharge Coefficients for Window Openings in Wind Driven Natural Ventilation. *International Journal of Ventilation, Marc 2016, vol. 5, nº 1*, pp. 43-52

[12] Grosso, M. Il raffrescamento passivo degli edifici. Ed.

[13] Palme, M., Inostroza, L., Villacreses, G., Lobato, A., Carrasco, C. From Urban Climate to Energy Consumption. Enhancing building performance simulation by including the urban heat island effect. Submitted to Energy and Buildings (in press).

[14] Palme, M., Inostroza, L., Villacreses, G., Lobato, A., Carrasco, C. Urban climate in the South-American coastal cities of Guayaquil, Lima, Antofagasta and Valparaiso and its impacts on the buildings’ energy efficiency. In Urban Climate in South America, Springer Ed. (in press)

[15] Palme, M., Carrasco, C., Lobato, A. (2016) Quantitative Analysis of Factors Contributing to Urban Heat Island Effect in Cities of Latin-American Pacific Coast. Procedia Engineering 169, 199-206

[16] Sailor, D. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 28 (9), 2003, 941-951

[17] Palme, M. (2016). The possible shift between heating and cooling demand of buildings under climate change conditions: are some of the mitigation policies wrongly understood? In Proceedings of the Mediterranean Green Buildings and Renewable Energy Conference, Springer Ed.

[18] Jenkins, D.P., Peacock A. D., Banfill, P.F.G., Will future low-carbon schools in the UK have an overheating problem?, *Building and Environment, Volume 44, Issue 3*, March 2009, Pages 490-501, ISSN 0360-1323

[19] Toledo, L., Cropper, P., Wright, A. (2016). Unintended consequences of sustainable architecture: Evaluating overheating risks in new dwellings. En: Proceedings of the Passive and Low Energy Architecture Conference, Los Angeles, USA, July 2016.

[20] Inostroza, L., 2014. Open Spaces and Urban Ecosystem Services. Cooling Effect towards Urban Planning in South American Cities. *Tema. Journal of Land Use, Mobility and Environment*. 