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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.

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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:

$$SGO = R \times S \times \alpha \times R_{es} \times U \quad (1)$$

where:

- SGO is the solar gain through the opaque envelope elements (J)
- R is the incoming solar radiation (J/m^2)
- S is the surface of the opaque element (m^2)
- α is the solar absorption of the surface
- R_{es} is the external surface thermal resistance (m^{2}K/W)
- U is the transmittance of the element (W/Km^2)

The second term is:

$$SGW = R \times S \times f_f \times f_{sg} \times f_{mp} \times f_a \quad (2)$$

where:

- SGW is the solar gain through the windows (J)
- R is the incoming solar radiation (J/m^2)
- S is the surface of the element (m^2)
- 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:

$$IG = \sum P \times S \times t \quad (3)$$

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 (m^2)
- t is the time of functioning or occupation (s)

The total gain is expressed by:

$$TG = IG + \sum SGO + \sum SGW \quad (4)$$

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

$$OH = TG - (T - T_A) \times H_t \times \eta \quad (5)$$

where

- T_A is the daily average temperature (ºC)
- T is the internal temperature (set as adaptive comfort temperature)
- H_t is the thermal loss (J/ºC) by transmission trough the envelope
- η 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:

$$T = \max(0.35\, T_A + 17.8\,; 26) \quad (6)$$

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 Valparaíso).

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/m^2)	North (MJ/m^2)	South (MJ/m^2)	East (MJ/m^2)	West (MJ/m^2)	Ta night (°C)	Ta 24h (ºC)	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
Valparaíso	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:

$$NVH = (T - T_v) \times (H_v) \times \eta \quad (7)$$

where:

- NVH is the heat removed by natural ventilation (J)
- T_v is the air temperature (daily average or 8-20 average depending on the case) (ºC)
- H_v is the thermal loss (J/ºC) by ventilation
- η is the efficiency of the heat loss

The thermal loss by ventilation is expressed as:

$$H_v = t \times \delta \times sh \times q \quad (8)$$

where:

- t is the period (s)
- δ is the density of the air (kg/m^3)
- sh is the specific heat of the air (J/kgK)
- q is the flow (m^3/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:

$$q = v \times \sqrt{\frac{|c_{p,i} - c_{p,o}|}{\frac{1}{c_{d,i}^2 \times s_i^2} + \frac{1}{c_i^2 \times s_d^2} + \frac{1}{c_{d,o}^2 \times s_o^2}}} \quad (9)$$

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

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

$$FRH = OH - NVH \quad (10)$$

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 (m^2)	H/W	L/W
House	3.5	10	7	70	0.5	1.43
Windows	1	1	na	1	na	na

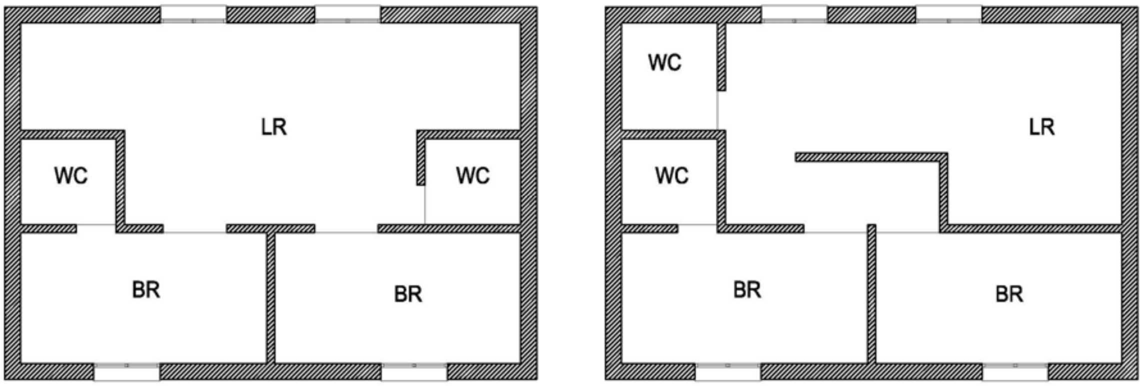

Figure 1: two houses, representative of a well-connected and of a poorly connected distribution.

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 m^3/s	0.30	0.18 m^3/s
House 90°	0.70	-0.20	0.70	1.00	0.80	0.44 m^3/s	0.30	0.25 m^3/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]. Valparaíso and Guayaquil have higher UHI intensities (up to 10 ºC during some nights in the case of Valparaíso).

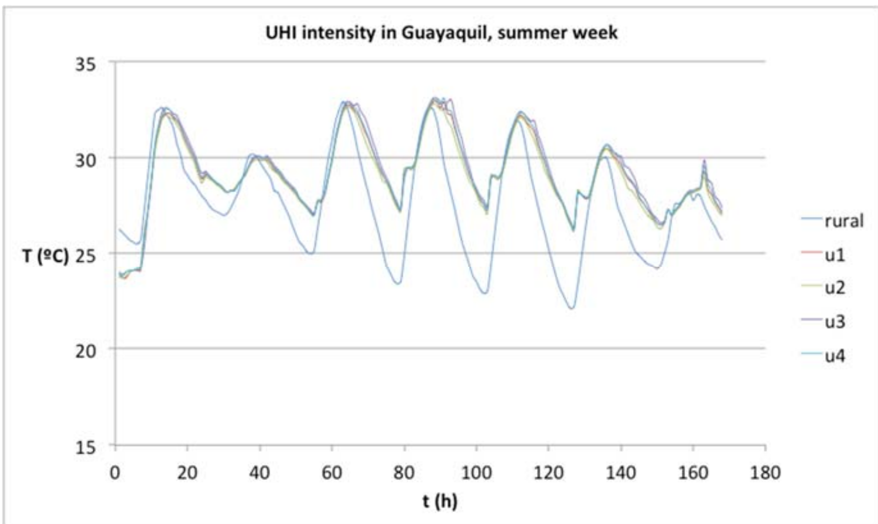

Figure 2: UHI intensity in Guayaquil during a summer week

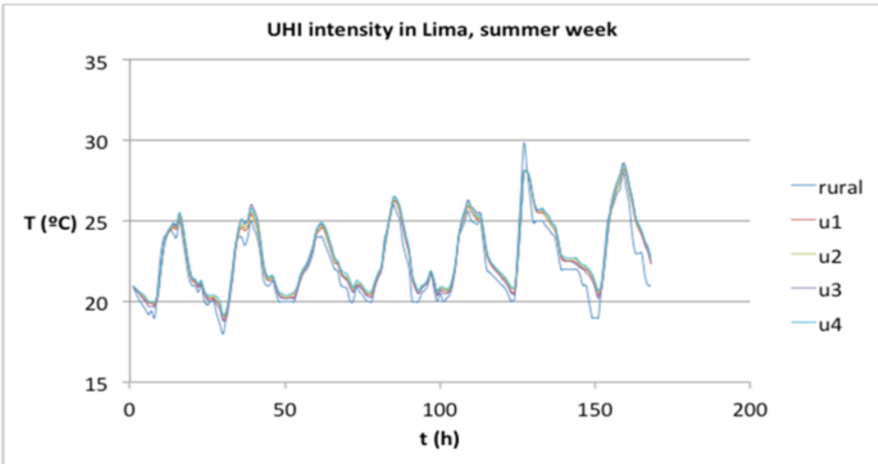

Figure 3: UHI intensity in Lima during a summer week

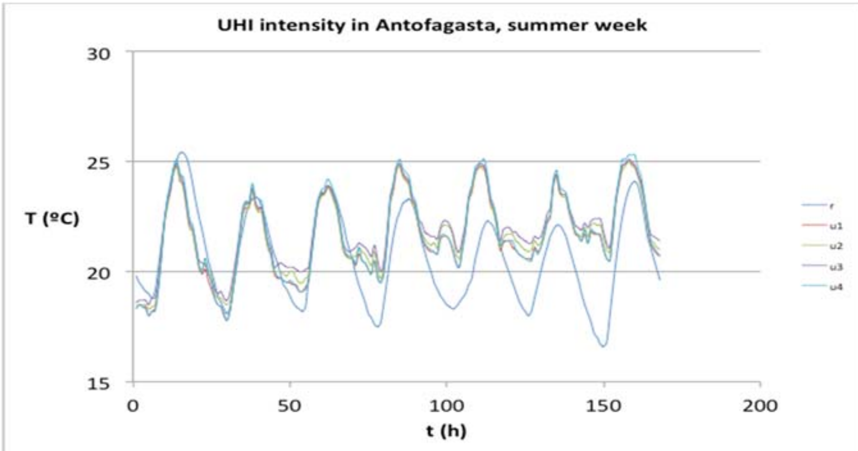

Figure 4: UHI intensity in Antofagasta during a summer week

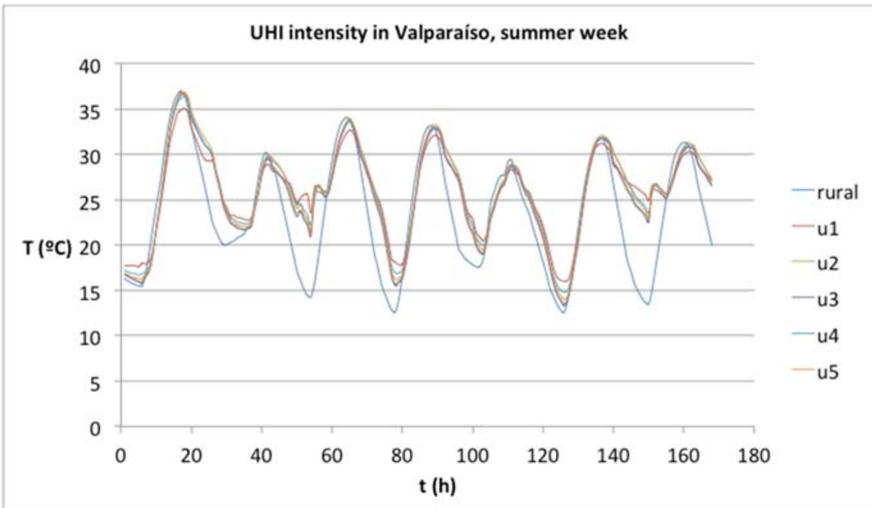

Figure 5: UHI intensity in Valparaíso during a summer week

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 90º (wc)	9,186 MJ	297 MJ	96 %	9,454 MJ	351 MJ	95 %
House 90º (pc)	9,186 MJ	1,677 MJ	82 %	9,454 MJ	1,892 MJ	80 %
House 45º (wc)	9,186 MJ	966 MJ	89%	9,454 MJ	1,111 MJ	88 %
House 45º (pc)	9,186 MJ	3,144 MJ	66 %	9,454 MJ	3,441 MJ	63 %
GUAYAQUIL						
House 90º (wc)	17,451 MJ	13,428 MJ	23 %	19447 MJ	18,477 MJ	5 %
House 90º (pc)	17,451 MJ	15,157 MJ	13 %	19447 MJ	18,893 MJ	3 %
House 45º (wc)	17,451 MJ	14,606 MJ	16 %	19447 MJ	18,761 MJ	4 %
House 45º (pc)	17,451 MJ	15,829 MJ	9 %	19447 MJ	19,055 MJ	2 %
ANTOFAGASTA						
House 90º (wc)	5,954 MJ	37 MJ	99 %	7,226 MJ	75 MJ	99 %
House 90º (pc)	5,954 MJ	301 MJ	95 %	7,226 MJ	562 MJ	92 %
House 45º (wc)	5,954 MJ	147 MJ	97 %	7,226 MJ	284 MJ	96 %
House 45º (pc)	5,954 MJ	768 MJ	87 %	7,226 MJ	1,322 MJ	82 %
VALPARAÍSO						
House 90º (wc)	7,325 MJ	85 MJ	99 %	13,323 MJ	2,823 MJ	79 %
House 90º (pc)	7,325 MJ	626 MJ	91 %	13,323 MJ	6,677 MJ	50 %
House 45º (wc)	7,325 MJ	320 MJ	96 %	13,323 MJ	5,254 MJ	60 %
House 45º (pc)	7,325 MJ	1,444 MJ	80 %	13,323 MJ	8,562 MJ	35 %
NOCTURNAL VENTILATION						
LIMA						
House 90º (wc)	9,186 MJ	2,491 MJ	73 %	9,454 MJ	2,593 MJ	72 %
House 90º (pc)	9,186 MJ	3,251 MJ	65 %	9,454 MJ	3,486 MJ	63 %
House 45º (wc)	9,186 MJ	2,788 MJ	70 %	9,454 MJ	2,964 MJ	69 %
House 45º (pc)	9,186 MJ	4,332 MJ	53 %	9,454 MJ	4,637 MJ	51 %
GUAYAQUIL						
House 90º (wc)	17,451 MJ	9,251 MJ	47 %	19447 MJ	14,836 MJ	24 %
House 90º (pc)	17,451 MJ	12,774 MJ	27 %	19447 MJ	16,817 MJ	13 %
House 45º (wc)	17,451 MJ	11,652 MJ	33 %	19447 MJ	16,186 MJ	17 %
House 45º (pc)	17,451 MJ	14,144 MJ	19 %	19447 MJ	17,587 MJ	10%
ANTOFAGASTA						
House 90º (wc)	5,954 MJ	3,603 MJ	39 %	7,226 MJ	3,359 MJ	53 %
House 90º (pc)	5,954 MJ	3,016 MJ	49 %	7,226 MJ	3,035 MJ	58 %
House 45º (wc)	5,954 MJ	3,196 MJ	46 %	7,226 MJ	3,079 MJ	57 %
House 45º (pc)	5,954 MJ	2,942 MJ	50 %	7,226 MJ	3,275 MJ	55 %
VALPARAÍSO						
House 90º (wc)	7,325 MJ	1,847 MJ	75 %	13323 MJ	7,282 MJ	45 %
House 90º (pc)	7,325 MJ	1,948 MJ	74 %	13323 MJ	9,394 MJ	29 %
House 45º (wc)	7,325 MJ	1,817 MJ	75 %	13323 MJ	8,583 MJ	36 %
House 45º (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 Valparaiso, 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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