Potential of buried pipes systems and derived techniques for passive cooling of buildings in Brazilian climates

Pierre Hollmuller [1)], Joyce Carlo [2)], Martin Ordenes [2)],
Fernando Westphal [2)], Roberto Lamberts [2)]

1) Centre universitaire d'étude des problèmes de l'énergie (CUEPE)
Université de Genève – Switzerland

2) Laboratório de Eficiência Energética em Edificações (LABEEE)
Universidade Federal de Santa Catarina – Brazil

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RESUMO EXECUTIVO

O objetivo deste estudo é avaliar o potencial de duas estratégias de ventilação inercial (tubos enterrados e defasador térmico) para resfriamento passivo de edificações sujeitas a diversos climas brasileiros. Numa primeira etapa foi caracterizado o potencial de resfriamento, independente do tipo de edificação, para os climas das cidades de Rio de Janeiro, Recife, Brasilia, São Paulo, Florianópolis e Porto Alegre. Numa segunda etapa foi avaliada a resposta térmica de dois protótipos de edificações, comerciais e residenciais, para os climas de São Paulo e Porto Alegre.

Ambas as técnicas estudadas utilisam um tipo de inercia térmica, exterior à estrutura das edificações, para armazenar a oscilação térmica noite/dia do ar externo que é utilisado para a ventilação. Os sistemas considerados são:

- Tubos enterrados sob a edificação, pelos quais se força mecanicamente o fluxo de ar, de forma a amortecer a oscilação diária e evitar picos de temperatura no período diurno. Derivações dessa técnica tem sido aplicadas através dos séculos para pré-aquecimento ou resfriamento. Recentemente, uma versão moderna foi desenvolvida na Europa, englobando construção e análise crítica de instalações piloto e de demonstração, assim como produção de ferramentas de simulação e regras práticas para engenheiros.
- Defasador térmico, um sistema de armazenamento do tipo leito de rochas de dimensões bastante precisas e com melhoria nas trocas convectivas. É uma nova técnica relacionada à já descrita troca de calor entre ar e materia, mas baseada na descoberta recente de um fenômeno físico simples. Se trata dessa vez de deslocar o pico de temperatura ao longo das horas, quase sem amortecimento, para que o pico noturno de baixa temperatura seja disponivel durante o dia. Uma série destes protótipos tem sido desenvolvida na Universidade de Genebra.

Ao amortecer ou atrasar os picos de temperatura, essas técnicas de ventilação inercial permitem uma melhor distribuição do potentcial de resfriamento na edificação durante o período diurno. Potencialmente, isso oferece uma vantagem às edificações até então incapazes de estocar o resfriamento noturno em sua própria estrutura.

A primeira etapa do estudo consiste na caracterização do potencial de resfriamento destas técnicas, independente do tipo de edificação, em termos de graus-hora relativa à temperatura considerada de conforto. Foi observado que :

- Em climas quentes como no Rio de Janeiro e no Recife, a ventilação inercial não apresenta benefícios para temperaturas de conforto de 26 °C. Mesmo definindo uma temperatura de conforto de 28 °C o potencial de resfriamento continua baixo: nos meses mais quentes (Janeiro e Fevereiro) o potencial de resfriamento durante o dia é inferior a 30 K.h/dia (10 kWh/dia por 1000 m3/h de ar);
- Os climas de Brasília, São Paulo, Florianópolis e Porto Alegre apresentam condições mais favoráveis: para uma temperatura de conforto de 28 °C o potencial de resfriamento durante o dia atinge, em média anual, de 90 a 120 K.h/dia (30 a 40 kWh/dia por 1000 m3/h de ar), dependendo da estrategia escolhida;
- Esses resultados differem ao avaliar somente os meses mais quentes (Janeiro e Fevereiro). Enquanto o potencial persiste para São Paulo e Brasilia, com 70 a 90 K.h/dia, ele diminui drasticamente para as cidades de Florianópolis e Porto Alegre, com apenas 40 a 60 K.h/dia.

Na segunda etapa, foi avaliada a resposta térmica de dois protótipos de edificações (residencial e comercial) considerando-os em duas situações: com ou sem climatização. As diferentes configurações foram simuladas no programa EnergyPlus para as condições climáticas das cidades de São Paulo e Florianópolis. As principais conclusões desta etapa são:

Para uma edificação sem ar condicionado:

- O uso de elementos de proteção solar para a envoltória da edificação deve sempre ser a primeira medida a ser adotada. Em seguida, pode-se pensar nas técnicas de resfriamento passivo;

- Em climas com uma importante amplitude de oscilação dia/noite, uma edificação sem ar condicionado, com cargas internas moderadas e proteção solar efficiente pode se beneficiar da ventilação inercial com uma redução nas temperaturas extremas de 1 a 3 °C, dependendo na estratégia de ventilação adotada;
- Como as técnicas de ventilação inercial se baseiam no armazenamento da oscilação dia/noite de temperatura externa, elas dependem na temperatura média diária. Assim, encontram-se limitadas nas semanas mais quentes do ano, durante quais a temperatura interna da edificação atinge valores acima de 26 °C em São Paulo, e acima de 28 °C em Florianópolis;
- A utilidade e a escolha de cada uma das estratégias depende do padrão de uso da edificação. Para o caso da edificação residencial (ocupação nocturna) o conforto térmico alcançado através da ventilação inercial é comparável aos resultados obtidos a partir da ventilação noturna direta. Por outro lado, na edificação comercial (ocupação diurna) observa-se um beneficio evidente no uso de ventilação inercial, em particular do defasador térmico;
- O consumo de energia elétrica para ventilação é um ponto importante a se analisar. Para a cidade de São Paulo, cujo clima é moderado, o consumo de energia para a ventilação inercial é finalmente comparável ao consumo de um sistema de ar condicionado eficiente. O consumo de energia poderia ser reduzido se o sistema de ventilação fosse utilizado durante os 6 meses mais quentes (em vez dos 9 meses mais quentes, como foi aplicado nas simulações). Entretanto, a limitação do consumo elétrico para a ventilação, em particular na distribução do ar na edificação, é um factor chave;

Para uma edificação com ar condicionado:

- O ar condicionado limita o uso da ventilação inercial como sistema de apoio, visto que nas semanas mais quentes esses sistemas não fornecem temperaturas abaixo de 24°C. Desse modo, não pode-se contar com sistemas de ventilação inercial para evitar os picos de cargas mais elevados;
- Todavia, existe um potencial de economia anual do ar condicionado, mas esse deve ser analisado junto com o consumo adicional para ventilação, em particular para o sistema de distribução.

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1. INTRODUCTION / OBJECTIVE

In Brazil as well as in Europe, air conditioning has been a straightforward response to excess heat in buildings. This rapidly growing trend not only induces important electricity consumption but also sharpens the load profile at peak hours, becoming an issue as well for electricity companies as for building owners.

As an alternative response to air conditioning, proper conception of building envelope (use of solar protections and thermal insulation, control of glazed area, adaptation of structure mass, use of natural lighting) may help to keep the building within the comfort zone (in free-float mode) or to reduce expected cooling load (in air-conditioning mode).

Further reduction or suppression of air conditioning may be achieved by using passive or low-energy cooling techniques. Two of such techniques will be investigated here. Both use inertia for active storage of the meteorological day/night temperature oscillation, and may be classified as inertial ventilation techniques :

- Use of buried pipes, which consists in forcing ambient air through the soil, underneath or next to the building, so as to dampen the daily oscillation and to avoid temperature peaks during daytime.
- Thermal phase-shifting, a newly developed technique based on recent discovery of a simple physical phenomenon. The air flow is now driven through a rock-bed type storage system of very precise dimension, which enables to delay the temperature peak over time almost without dampening, so that the cold temperature peak of the night be available in the middle of the day.

Objective of this study is to evaluate the potential of these inertial ventilation techniques for passive cooling of buildings in Brazilian climates. In a first step, this cooling potential will be characterized independently of any building dynamic, in terms of the available temperature differential relatively to a specified comfort set point. In a second step, the effective response of a residential as well as of a commercial building will be evaluated :

- in stand alone mode within a free-floating building, in terms of achievable comfort conditions (percentage of temperature overshoots within building).
- in backup mode of a traditional air-conditioning system, in terms of achievable electricity savings.

2. CLIMATES

This study will focus on six of the major Brazilian cities, on basis of standard meteorological data in hourly time step [Labeee 2006]. They may globally be characterized and differentiated in terms of their average temperature, as well as their yearly and daily temperature amplitudes (Fig. 1 and Tab. 1). In terms of cooling, they may further be characterized by their temperature overshoots during day / night periods (6 – 18 h / 18 – 6 h), as evaluated over the whole year or merely over January and February, the hottest two months (Fig. 2).

Tab. 1 : Main climatic zones, temperature average and amplitudes .

Climatic zone				**Temperature**		
City	Latitude	Longitude	Altitude	Average	Year 1)	Day 1)
	S	W	m	C	K	K
Brasilia	15°52'	47°56'	1171	20.7	3.2	9.5
SãoPaulo	23°37'	46°39'	760	18.8	5.4	7.0
Rio de Janeiro	22°50'	43°15'	2	23.6	6.0	5.0
Recife	8°08'	34°55'	4	25.7	2.6	3.0
Florianopolis	27°40'	48°33'	3	20.7	7.7	5.7
Porto Alegre	30°00'	51°11'	3	19.2	10.6	8.0

1) Average year and day amplitude, as given by Fourier analysis of hourly data over one year.

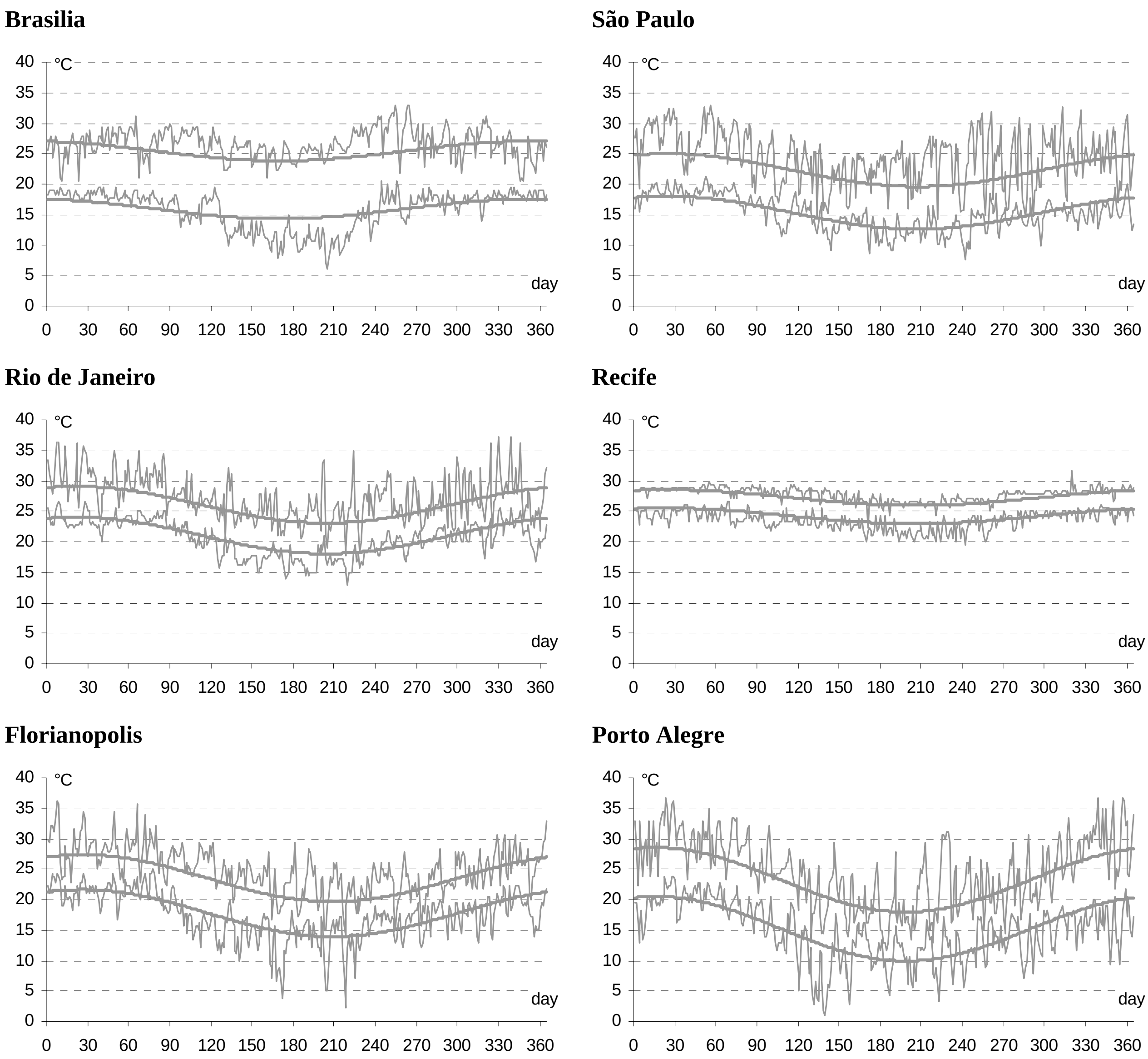


Fig. 1 : Daily ambient temperature extremes over one year, in dynamic form as given by standard hourly data (thin lines), as well as in average form thereof as given by Fourier analysis (thick lines).

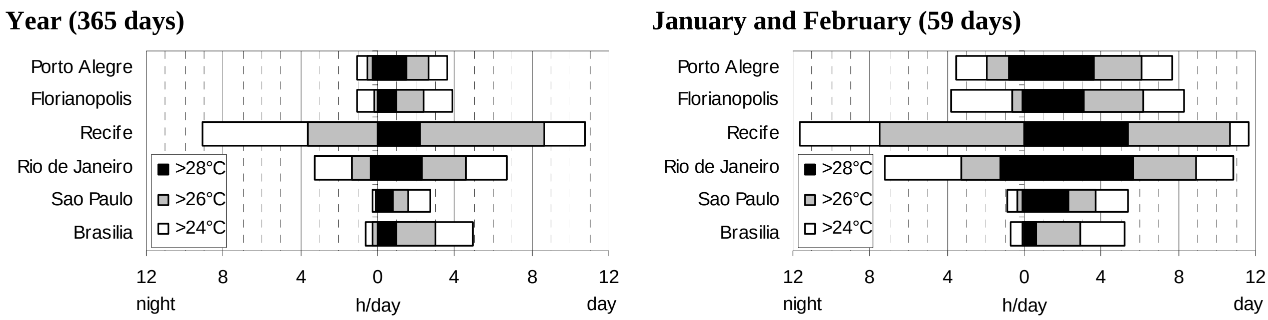


Fig. 2 : Ambient temperature overshoots during day / night periods (6 – 18 h / 18 – 6 h), over the whole year and over the hottest months.

For the purpose of our study we hence will keep in mind following simplified classification :

- Situated on the coast, Recife and Rio de Janeiro are the hottest of these cities, with small seasonal as well as daily amplitudes. Most hours of the year exceed 24°C, during day as well as during night, and over the hottest months half of the diurnal hours exceed 28°C.
- Situated off the coast and somewhat in altitude, Brasilia and São Paulo have milder average temperatures along with more important daily amplitudes, but still relatively small seasonal variations. As a consequence, temperature overshoots are only diurnal, and much less frequent than for the preceding cities.
- Situated south of the tropic of Capricorn, on the coast, Florianopolis and Porto Alegre have more important seasonal variations than Brasilia and São Paulo, for similar average temperatures and daily amplitudes. Temperature overshoots hence remain similar when evaluated over the whole year, but get more important when evaluated merely over January and February, the hottest two months.

3. INERTIAL VENTILATION

3.1. Buried pipes

State of art

An air/soil heat exchanger consists of a set of buried pipes situated at the entrance of the ventilation system, underneath or next to the building. Depending on the chosen geometry and dimension, it is used so as to dampen the daily or the yearly meteorological oscillation, so as to avoid corresponding hot or cold temperature peaks. Although derivatives of it have been applied over centuries in more or less traditional forms, a modern revival of the technique has been manifest in Europe over the last decade, with construction and critical analysis of pilot and demonstration installations as well as production of simulation tools and thumb rules for engineers [Hollmuller 2002; Hollmuller et al 2005a].

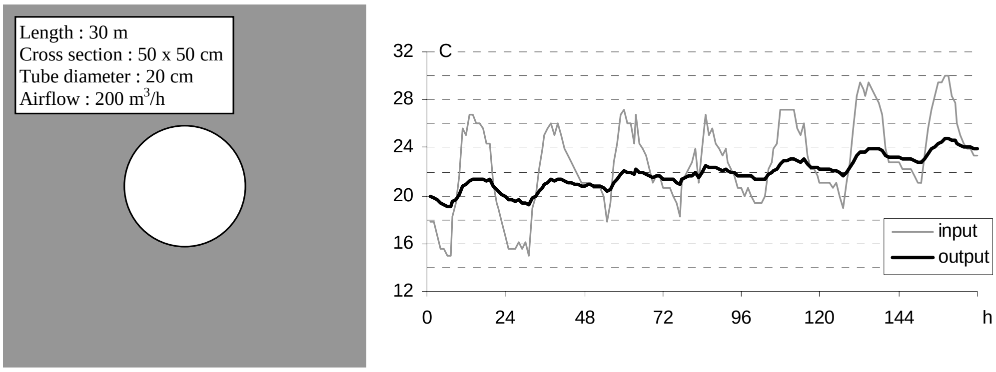
It can in particular be shown that dampening of the daily temperature oscillation can be achieved with barely 15-20 cm earth around the pipes, enabling for compact and cost-efficient systems (possibly in multi-layer, as will be used through out this study). With such a compact array, complete dampening is achieved with about 1 m^2 tube exchange surface for each 5-15 m^3/h of airflow, depending on pipe diameter and air velocity (1-4 m/s). In mid-European climates, with summers characterized by diurnal overshoots but average daily temperatures usually within the 20-26°C comfort zone, such a system yields comfortable ventilation temperatures on a 24/24 h basis, which enables to evacuate heat loads from the building (if necessary with airflows enhanced up to several air change per hour, and correspondingly dimensioned pipes).

To the contrary, use of buried pipes for preheating of cold air during winter is a seasonal problem, which requires dampening of the yearly temperature oscillation. Latter however only gets possible with deeply and wide apart buried pipes, requiring some 2-3 m soil around each, in which case complete dampening is achieved with about 1 m^2 tube exchange for each 3-9 m^3/h of airflow, depending on pipe diameter and air velocity (1-4 m/s). Alternatively, a compact array of pipes as for diurnal dampening can also be used (but only single-layered), however also resulting in a huge system, since complete yearly dampening in this case would require about 1 m^2 tube exchange surface for each 1 m^3/h of airflow.

System configuration

As yearly dampening of the meteorological oscillation would require too huge a system, throughout this study we will focus on a configuration for dampening of the daily meteorological oscillation (Fig. 3). In agreement with preceding rules, the selected configuration consists of a multi-layer array of pipes of 20 cm diameter and 30 m length, with 50 cm inter-axial distance, each treating a 200 m^3/h airflow. So as to account for the total airflow (9'900 m^3/h corresponding to 5 ach, see below), some 50 pipes need to be installed underneath the residential building, 12.5 m wide by 1 m deep, yielding a 375 m^3 excavation/storage volume. Similarly, in the case of the commercial building (15'600 m^3/h total airflow, corresponding to 5 ach), some 80 pipes need to be installed, yielding a 600 m^3 excavation/storage volume.

Buried pipes



Phase-shifter

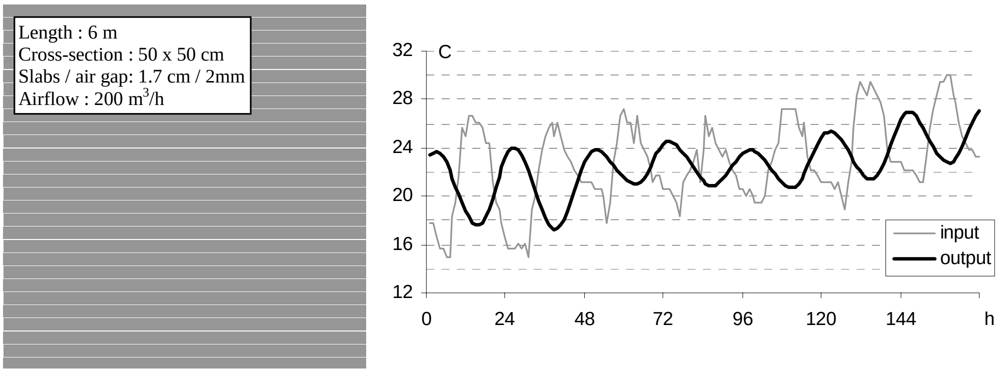


Fig. 3 : Inertial ventilation systems, typical elementary cross-section for 200 m^3/h airflow, as well as input and output temperatures on a typical summer week (Florianopolis, week no 52).

3.2. Thermal phase-shifter

State of art

Discovered by way of an analytical study on previously described buried pipes [Hollmuller 2003], thermal phase-shifting relates to previously described air/soil heat exchangers, but aims in delaying rather than dampening of the daily temperature oscillation carried by the airflow, so as to have the temperature peak of the night available in the middle of the day. A specific theoretical and experimental study allowed to understand the basic physical phenomenon, as well as to develop lab prototypes for complete 12 h phase-shifting of the daily meteorological oscillation [Hollmuller et al 2006].

The idea consists in forcing the airflow through a packed bed, which consists of thin and homogenous heat storage particles or layers. Making use of an enhanced exchange surface and of a small heat penetration depth, thermal phase-shifting then basically resumes in using the thermal inertia of the packed bed so as to slow down the temperature wavelength which is naturally carried by the air velocity.

On the experimental level, the development of lab prototypes, with different filling materials (ceramic balls or slabs, so as gravel), confirms the possibility of complete 12 h phase-shifting of the daily meteorological oscillation, with an order of magnitude of 1 m^3 storage material per 100 m^3/h airflow. The associated amplitude transmission may be as high as 80%, but varies strongly from one configuration to the other, in particular because of non homogenous airflows, in relation with non homogenous particle geometries or pilling up.

System configuration

Throughout this study we will focus on one of the developed lab prototypes, which consists of piled up 1.7 cm thick ceramic slabs with a 2 mm air gap between them (Fig. 3). For a 200 m^3/h airflow, a 50 x 50 cm cross-section of 6 m length allows for complete 12 h phase shifting of the daily temperature oscillation, with a 60% amplitude transmission. This corresponds to 5 times less storage volume than for the buried pipe configuration, resulting in about 75 m^3 for 5 ach ventilation of the residential building, and 120 m^3 for the commercial building.

3.3. Simulation tool

Simulation of the above defined inertial ventilation systems occurs by way of a specially developed tool, which bases on Fourier analysis of hourly meteorological data over one year. Computation of the system output occurs by way of a complete analytical solution for a constant airflow with harmonic input temperature, taking into account convective heat exchange between the air and the pipe or slab, as well as heat diffusion within the soil [Hollmuller 2003]. The tool was extensively validated against experimental data as well as against a finite difference numerical simulation model [Hollmuller and Lachal 2005].

4. COOLING POTENTIAL

4.1. Controlled ventilation strategies

As seen before, both inertial ventilation techniques under consideration are based on thermal storage of the meteorological day/night temperature oscillation, which requires a constant 24/24h driven airflow through the storage medium (buried pipes or phase-shifter). Enhanced ventilation of the building for cooling purposes however only makes sense when the temperature at storage output is effectively lower than in the building (as is also the case for direct ventilation from ambient, usually only activated at night). In warm climates it hence will be beneficial to use inertial ventilation with a simple thermal controller and an exhaust valve at storage output (Fig. 4, left), for the warm air to be driven back to ambient during critical periods (in particular so for thermal phase-shifting, with temperature peaks not dampened out but only delayed in time).

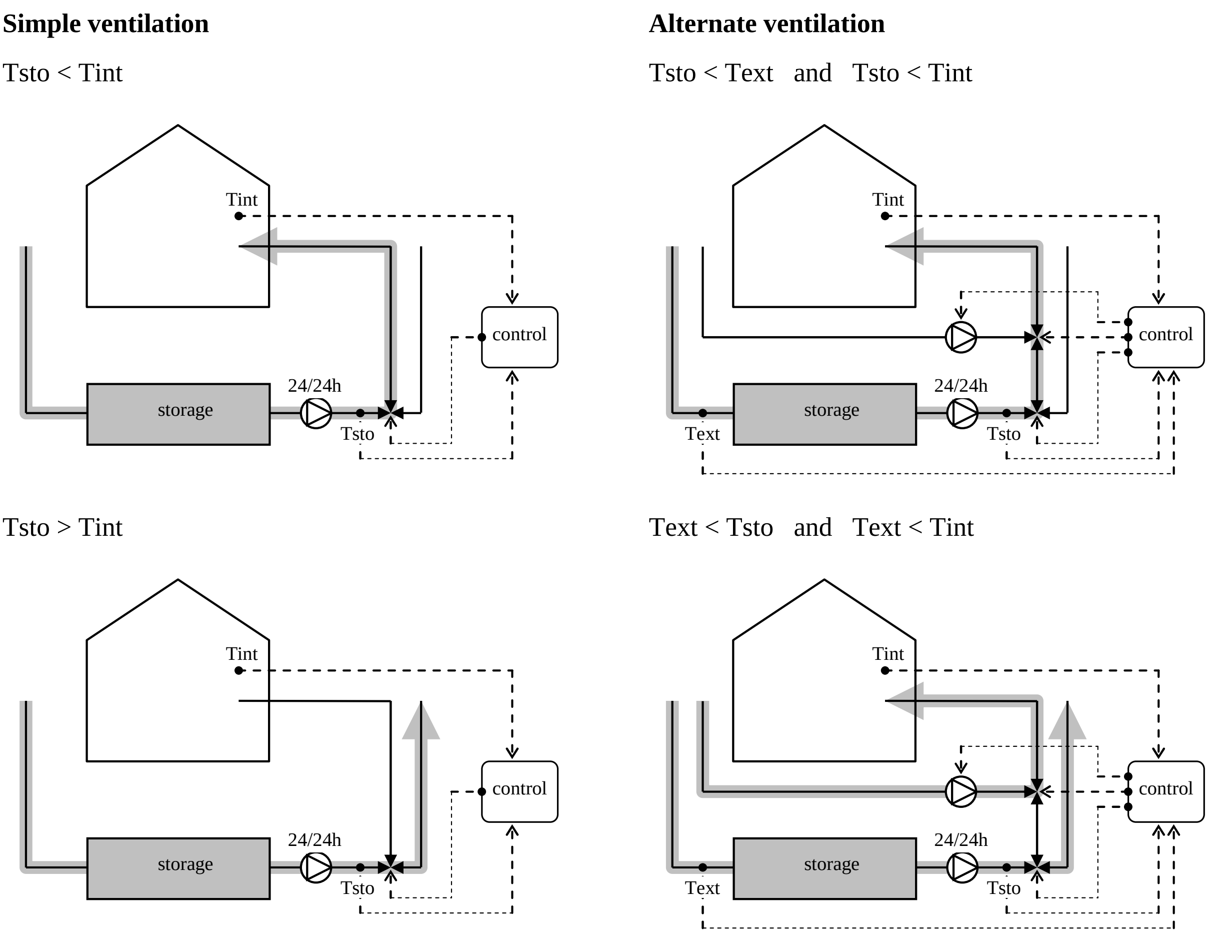


Fig. 4 : Inertial ventilation in simple or alternate mode.

So as to take further advantage of the fresh ambient at night, which is lower than at storage output (Fig. 3), use of an alternate ventilation strategy may also be considered, using whichever of the two sources presents a lower temperature (ambient or inertial storage). Since ventilation through the inertial storage has to be maintained 24/24h, such a strategy however requires a storage bypass and a specific fan for direct ventilation from ambient (Fig. 4, right).

Following ventilation strategies (to be identified with following acronyms) will hence be evaluated :

- Controlled direct ventilation from ambient (Dir).
- Controlled inertial ventilation with buried pipes, in simple mode (Pipe) as well as in alternate mode (PipeDir).
- Controlled inertial ventilation with phase-shifter, in simple mode (Shift) as well as in alternate mode (ShiftDir).

4.2. Dynamic on a typical summer week

In a first step, the cooling potential of these ventilation strategies may be characterized in relation to a specified comfort set point, which defines up to what acceptable temperature level the airflow shall be driven to the building or not. The resulting dynamic, on a warm but not very hot summer week, shows the advantages and disadvantages of the several strategies (Fig. 5 and Tab. 2) :

- When evaluated over the whole period, inertial ventilation techniques used in simple mode (Pipe and Shift) yield a cooling potential similar to that of direct ventilation (Dir). This similitude basically relates to the fact that both techniques are based on storage of the meteorological day / night oscillation.
- By dampening or differing of the oscillation peak, inertial ventilation however enables for better distribution or shift of the cooling potential towards the diurnal periods, yielding an advantage for buildings which could not store the cooling potential of the night within their proper thermal mass.
- In alternate mode, inertial ventilation (PipeDir and ShiftDir) allows to take double advantage of the cooling peak, directly at night and again in a dampened / shifted way during day time. This advantage however only will be effective as far as the cooling necessity actually does extend over the 24 h period, or as long as the direct cooling potential of the night may be stored within the building thermal mass.
- For all of the strategies, the weight of the acceptable comfort set point on the cooling potential has to be stressed : the harsher the requirement, the less direct or inertial ventilation will be suitable for cooling purposes.
- Similarly, the dependence upon the average daily temperature is a major limitation, in particular so for low comfort set points : during hot periods, latter can not even be reached at level of ventilation, not speaking about the building itself.

Tab. 2 : Cooling potential over a warm summer week (Florianopolis, week no 52).

Config	Total (0-24h)			Day (6-18h)		
	$\Delta T_{24°C}$ K.h/day	$\Delta T_{26°C}$ K.h/day	$\Delta T_{28°C}$ K.h/day	$\Delta T_{24°C}$ K.h/day	$\Delta T_{26°C}$ K.h/day	$\Delta T_{28°C}$ K.h/day
Dir	51	86	128	3	11	25
Pipe	52	99	147	17	37	57
PipeDir	68	115	163	17	37	57
Shift	43	85	132	31	51	71
ShiftDir	83	131	179	31	51	71

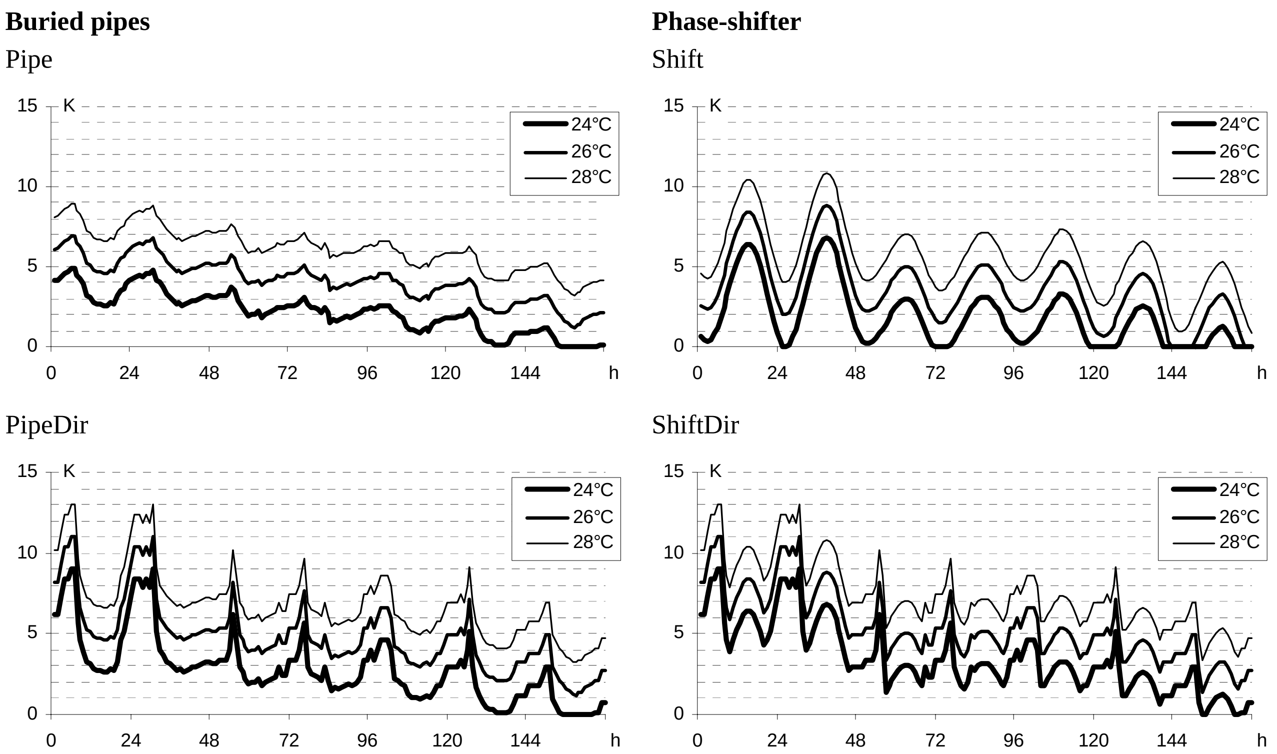


Fig. 5 : Cooling potential of inertial ventilation strategies relatively to different comfort thresholds, hourly dynamic over a warm week (Florianopolis, week no 52).

4.3. Average cooling potential

In a more synthetic way, the various strategies may be characterized in terms of the daily average of this cooling potential during day / night periods (6 – 18 h / 18 – 6 h), as evaluated over the whole year or merely over the hottest two months (Fig. 6) :

- In all cases, the effect of inertial ventilation pointed out above is obvious : by dampening or differing of the oscillation peak, inertial ventilation enables for better distribution or shift of the cooling potential towards the diurnal periods, yielding an advantage for buildings which could not store the cooling potential of the night within their proper thermal mass.
- Obviously, the combination of inertial ventilation with direct ventilation (PipeDir and ShiftDir) always shows a higher potential than inertial ventilation in stand alone mode (Pipe and Shift).
- However, because of their hot climate, Rio de Janeiro and Recife may not count with inertial ventilation for cooling below 26°C. Even with a set point at 28°C, cooling potential remains extremely low : during hottest months less than 30 K.h/day over day time (corresponding to less than 10 kWh/day per 1000 m3/h air).
- When averaged over the whole year, all other cities bear more reasonable but still limited values : for a set point at 28°C, depending on the ventilation strategy, 90 – 120 K.h/day over day time (30 – 40 kWh/day per 1000 m3/h air) and approximately twice as much over 24h. Furthermore, because of somewhat milder average temperatures, the yearly average cooling potential still exists for a set point at 24°C.
- The situation is somewhat different when evaluated over the hottest months only (January and February). Whereas the cooling potential persists almost unchanged for São Paulo and Brasilia, with 70 – 90 K.h/day, latter is not the case any more for Florianopolis and Porto Alegre, with 40 – 60 K.h/day, because of higher summer temperatures due to a stronger seasonal dynamic.

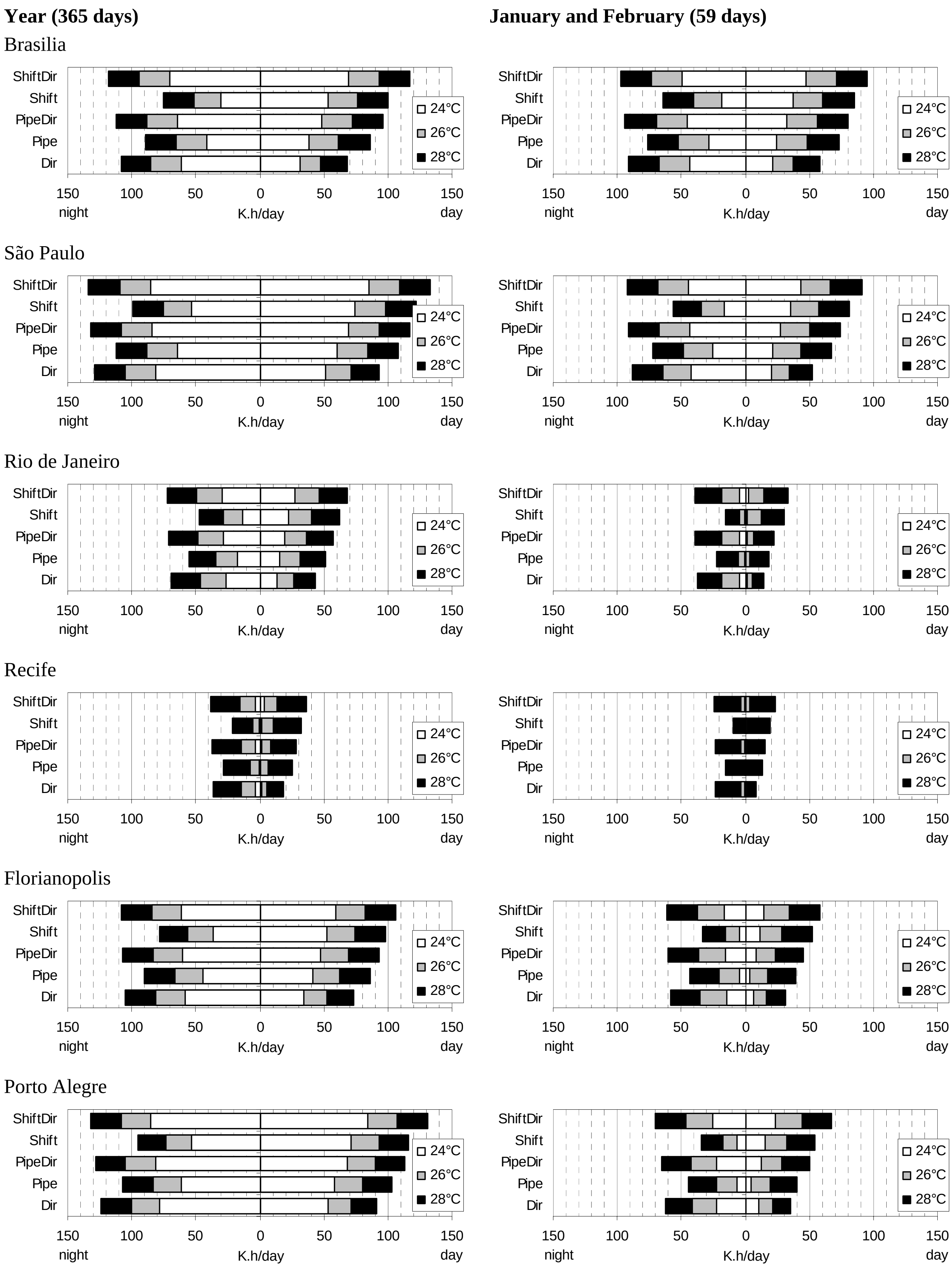


Fig. 6 : Cooling potential of direct and inertial ventilation strategies relatively to different comfort thresholds, overall values over the whole year and the two hottest months (left and right), during day / night periods (6 – 18 h / 18 – 6 h).

5. BUILDING

As already pointed out, the usefulness of previously described cooling potential depends on the effective cooling needs of the building, which in turn depend on the building envelope (in particular thermal mass and solar protection), the internal loads, as well as the period of the day on which comfort conditions have to be attained (occupancy).

This chapter will explore the effective building response to the different ventilation strategies, either in terms of temperature overshoots in free-floating mode, or in terms of electricity savings in air-conditioning mode, both for a residential and a commercial building.

Because of the poor cooling potential in the hot climatic zones (Rio, Recife), as well as necessity to limit the number of studied cases, this analysis will only concern the cities of São Paulo and Florianopolis.

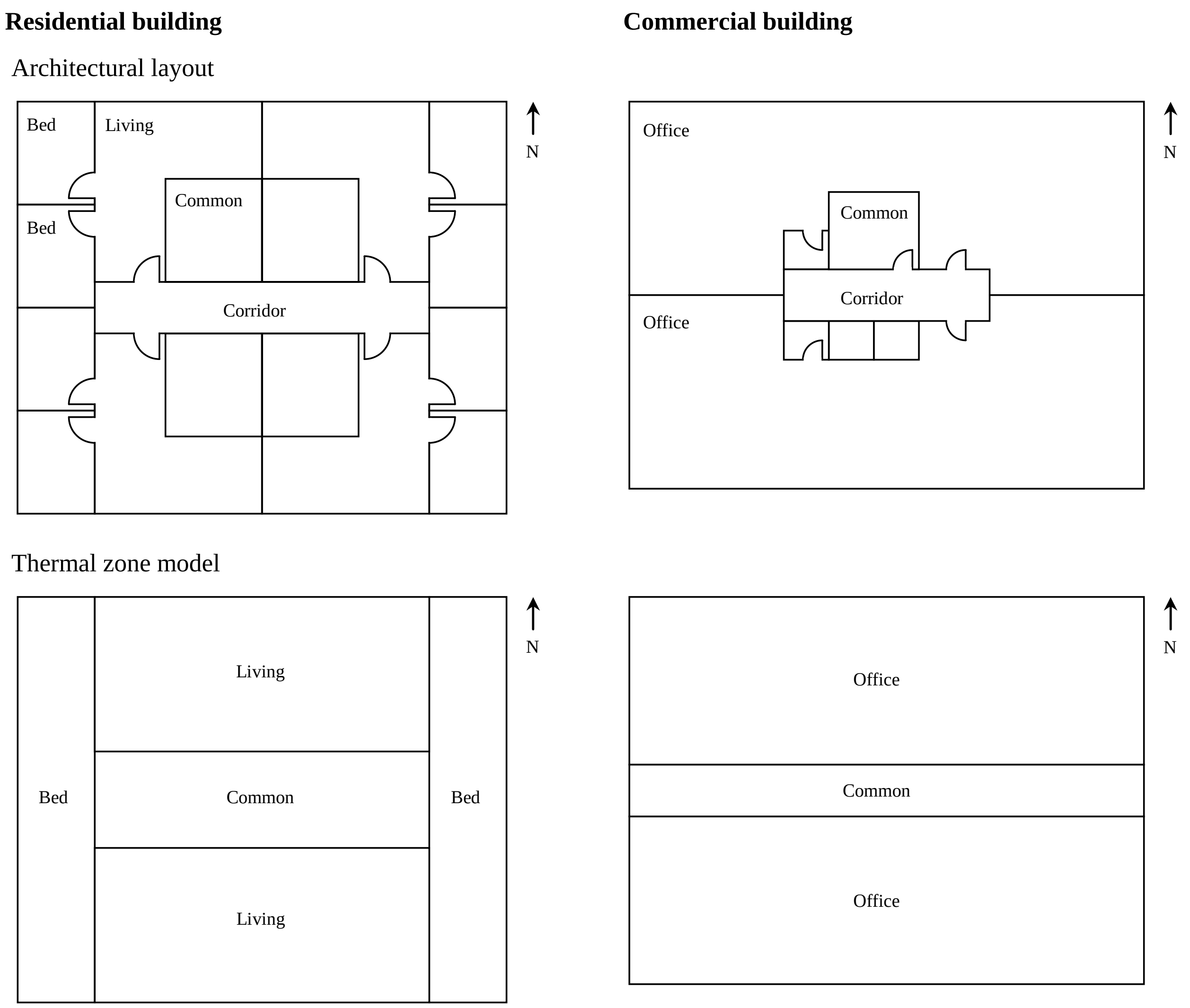


Fig. 7 : Building layout and thermal zone model.

5.1. Residential building

Architectural and thermal characteristics

The residential building under consideration (Fig. 7) is a typical low-cost residential building as massively constructed all over the country, representing 15% of the constructed multi-dwelling buildings for middle class revenue [Tavares, 2003]. It consists of 4 floors, each of 2.8 m height, on a ground area of 16 x 19 m. Each floor is divided into 4 flats, each consisting of one living room (20 m^2), two bedrooms (12 m^2 each), a kitchen (10 m^2) and a bathroom (5 m^2). This layout is described by way of a simplified thermal model of 5 zones per floor : two for the living rooms, facing respectively north and south (2 x 40 = 80 m^2), two for the bedrooms, facing respectively east and west (2 x 48 = 96 m^2) and one for the commons and the corridor (128 m^2).

Thermal and constructive characteristics are as follows :

- External walls (24 cm) are made of concrete blocks and mortar, with a thermal capacity of 280 kJ/K.m^2 and an overall U-value of 4.5 W/ K.m^2 (convective exchange not included).
- As a preliminary thermal measure, although unusual for such buildings, the roof includes a 5 cm thermal insulation and an air space, for an overall U-value of 0.7 W/ K.m^2 (convective exchange not included).
- Windows are made of simple 3 mm clear glazing. The window to wall ratio is 17.9%, corresponding to a window to floor ratio of 16.7% (9.5% when taking into account commons and corridors).
- Unlike for typical constructions of this type but as an additional constructive cooling measure, fixed shading devices on the facades are designed to cut off excessive solar gains. For the sake of comparison, a configuration without shading will however also be considered.
- Infiltration rate is 1.5 ach, in free-floating as well as in air-conditioning mode. This constant value is maintained along with inertial or direct ventilation. For the sake of comparison, a configuration with tighter envelope (0.5 ach) will also bee considered.

Occupancy, internal loads and hvac setpoints

Occupancy is supposed to extend from mid afternoon to early morning, schematically divided in a first period within the living rooms (14 – 22h) and a second period within the bedrooms (22 – 7h), with following internal loads:

- In the living rooms : an average of 30 W/m^2 during the first 8 h period (of which 80% due to 4 persons/flat).
- In the bedrooms : an average of 15 W/m^2 during the second 9 h period (of which 90% due to 5 persons/flat).
- In the commons : an average of 17 W/m^2 during the first 8 h period (of which 87% due to to equipment and lights, the rest due to 1 person/flat) and a constant 2 W/m^2 during the other 16 h (only equipment).

Although air-conditioning is nowadays not yet affordable for population of such buildings, its generalization might give raise to important energy consumption. Alternatively to the free-floating mode, we will hence also consider cooling and heating with individual fan coils in living and bedrooms. Upper and lower setpoints will be 18 and 24°C, as usual in Brazil when such hvac systems are available, and their use will be limited to the above defined occupancy periods.

5.2. Commercial building

Architectural and thermal characteristics

Very similar in shape (Fig. 7), the commercial building also consists of 4 floors, each of 3.0 m height, on a ground area of 15 x 20 m. Each floor is divided into two open-plan offices (130 m^2 each), facing north and south, and of a central area for corridor and commons (40 m^2). This simple layout defines the thermal zone model in a straightforward manner.

Very similar to the residential building, thermal and constructive characteristics are as follows :

- External walls (15 cm) are made of clay blocks and mortar, with a thermal capacity of 270 kJ/K.m2 and an overall U-value of 5.2 / K.m2 (convective exchange not included).
- The roof includes a 2.5 cm thermal insulation and an air space, for an overall U-value of 1.8 / K.m2 (convective exchange not included).
- Windows are made of simple 3 mm glazing. The window to wall ratio is 16.3% (in offices), corresponding to a window to floor ratio of 12.4 (10.7 when taking into account commons and corridors).

- As for the residential building, fixed shading devices on all facades are supposed to cut off excessive solar gains. For the sake of comparison, a configuration without shading will also be considered.
- As for the residential building, infiltration rate is 1.5 ach, in free-floating as well as in air-conditioning mode. This constant value is maintained along with inertial or direct ventilation. For the sake of comparison, a configuration with tighter envelope (0.5 ach) will also bee considered.

Occupancy, internal loads and hvac setpoints

Occupancy is supposed to extend over daytime only (8 – 18h), with following internal loads :

- In the offices : a constant 15 W/m2 during the 10 h occupancy period (of which 20% due to 10 persons/office, the rest due to equipment and light).
- In the commons : a constant 6 W/m2 during the 10 h occupancy period (only light).

Air-conditioning in the offices will only be active during occupancy, with same standard 18°C and 24°C setpoints as before. However, for the sake of comparison, all configurations will also be tested in free-floating mode.

5.3. Tested configurations

The thermal response of above defined buildings will be evaluated for following architectural configurations and ventilation strategies (Tab. 3) :

- A reference case (Base) consisting of above defined building, with shading devices and basic 1.5 ach infiltration, but without active ventilation.
- Two building alternatives, one without shading (NoShade), the other with a tighter 0.5 ach envelope (Tight), both without active ventilation.
- Controlled direct ventilation from ambient (Dir), for the base case building.
- Controlled inertial ventilation with buried pipes, in simple mode (Pipe) as well as in alternate mode (PipeDir), for the base case building.
- Controlled inertial ventilation with phase-shifter, in simple mode (Shift) as well as in alternate mode (ShiftDir), for the base case building.

For the last five configurations, controlled ventilation will be used at a rate of 5 ach (with storage dimension as described in Ch. 3), along with a standard 1.5 ach infiltration. Alternatively, ventilation at 10 ach has also been tested but hasn't shown major influence on the thermal response of the building, so that the results presented here may be regarded as effective potentials.

Tab. 3 : List of tested configurations.

Configuration	Shading	Infiltration	Ventilation source
Base	yes	1.5 ach	
NoShade	no	1.5 ach	
Tight	yes	0.5 ach	
Dir	yes	1.5 ach	direct
Pipe	yes	1.5 ach	pipes
PipeDir	yes	1.5 ach	buried pipes / direct
Shift	yes	1.5 ach	phase-shifter
ShiftDir	yes	1.5 ach	phase-shifter / direct

Ventilation at 5 ach is 9'900 m^3/h (residential building), respectively 15'600 m^3/h (commercial building).

5.4. Simulation tool and methodology

Simulation of the above defined configurations are carried out with Energy Plus (version 1.2.1.022), with following specific procedures and hypothesis :

- As is common for simulation of multi-floor buildings, latter are defined by way of three typical floors (hence with a total of 15 thermal zones for the residential building, 9 zones for the commercial building) : a bottom floor, with ground coupling as given by the software algorithm; a top floor, including coupling to ambient by way of above defined roof; finally a unique intermediate floor, with coupling to precedent floors.
- As version 1.2.1.022 of Energy Plus did not yet allow for ventilation of a thermal zone by way of data read from a file, a specific procedure for introduction of the temperatures from the separately simulated inertial ventilation systems was developed. The procedure consists in defining a virtual thermal zone, with an hourly defined temperature as given by inertial ventilation, and to define controlled ventilation from that zone to the actual thermal zones of interest.
- As well for São Paulo as for Florianopolis, constant 24/24 h inertial ventilation is activated from September to May, with injection into the building controlled separately for each thermal zone (except for commons, which are not ventilated). In real situation, such an individualized control might be limited by technical or economic questions, but allows here for determination of the optimized cooling potential.
- In air-conditioning mode, inertial ventilation is considered as a backup technology. Control of inertial ventilation occurs in the same way as in free-floating mode, accordingly to the zone – storage or zone – ambient differential, independently of the hvac system being on or off.
- Electricity consumption of the inertial ventilation system bases on charge losses in the thermal storage of 10 Pa (buried pipes), respectively 50 Pa (phase-shifter), as measured on different such systems. The main consumption however goes for air distribution in the building, which was estimated to be possible with 100 Pa. Latter value is also being retained for controlled direct ventilation, although latter strategy could also be used in a decentralized way.
- Electricity consumption of the hvac system bases on a COP of 3 for cooling and a fan consumption of 0.3 W per m^3/h air, corresponding to individual fan coils.

6. EFFECTIVE COOLING

6.1. Operation on a typical summer week

The hourly dynamic of the different strategies and the induced building response is depicted here for a warm but not very hot summer week (same week as in Ch. 4), in free-floating (Fig. 8-9) as well as in air-conditioning mode (Fig. 10-11). It is synthetically evaluated in terms of the average / maximum temperature during occupancy (in free-floating mode) and the total / maximum electricity load of the hvac-system (in air-conditioning mode), and is finally compared to the case of an extremely hot week (Tab. 4).

Free-floating mode

In a general way, following points characterize the free-floating mode :

- In the residential building, the distinct occupancy and internal loads of the living rooms (14 – 22h) and bed rooms (22 – 7h) results in somewhat separated zone temperatures, with an approximate 1 K increase in each zone during occupancy. In the commercial building, with same occupancy and load structure in both offices, such a distinction is not visible, despite the north / south orientation.
- With a somewhat less efficient envelope, and submitted to diurnal internal gains, the commercial building has slightly higher maxima than the residential building, for similar minima at night.

Over the specific warm but not very hot week under consideration, the different configurations yield following results :

- In absence of ventilation, the building temperature of the reference case (Base) rises along with the ambient temperature, with diurnal maxima reaching up to 27.1 / 28.2°C for the residential / commercial building.
- Absence of shading devices (NoShade) results in slightly higher temperatures, with a 0.4 / 0.8 K increase of the maxima.
- In absence of ventilation, a constantly tighter envelope (Tight) has almost no effect on the diurnal maxima, when building temperature is close to ambient. It however impedes relaxation during night, with a negative effect on the average temperature of the residential building at night, but it remains almost neutral for the commercial building.
- To the contrary, direct ventilation (Dir) enables to reach lower night temperatures in both buildings. Because of distinct occupancy schedules, this globally turns out beneficial for the residential, more than for the commercial building. The relatively low thermal mass however doesn't allow to store the cooling peak of the night into the building structure, so that for both buildings extreme temperature during occupancy are only lowered by some 0.3 K.
- By dampening and shifting of the airflow temperature, both inertial ventilation strategies used in simple mode (Pipe and Shift) bring about smoother temperature profiles in the buildings. Because of distinct schedules, the cooling effect on extreme temperatures during occupancy is however much more important for the commercial building (-2.0 K with buried pipes, -3.2 K with phase-shifting) than for the residential building (-0.8 K and -0.9 K). This discrepancy loses importance for average temperatures during occupancy.
- As expected, inertial ventilation in alternate mode (PipeDir and ShiftDir) brings about cooler building temperatures at night, along with smoothened peaks during daytime. As compared with inertial ventilation in simple mode, such strategies obviously are of no advantage for the commercial building. In the case of the residential building, the additional cooling effect is particularly important on the average temperatures, but in the case of phase-shifting to some extent also on the extreme temperature (-1.6 K).

Latter results finally bring about several comments :

- In a climate with important day/night oscillation, a free-floating building with reasonable internal loads and correct solar protections may benefit from inertial ventilation, with a reduction of the extreme building temperatures by 1 to 3 K, depending on the ventilation strategy. This is significantly more than for direct ventilation from ambient, which can not be stored in the building structure.
- The usefulness of this potential obviously depends on the occupancy schedule, which further determines which one of the strategies is most adequate.
- As pointed out before, these techniques are based on storage of the day/night ambient temperature oscillation and are hence limited by the daily average ambient temperature. This gets particularly clear when comparing the results of a warm and a hot week (Tab. 4), with extreme ambient temperatures of 30°C and 34°C respectively. With same temperature reductions as compared to the base case, inertial ventilation allows to keep the building below or close to 26°C during the warm week, compared to 30°C during the hot week.

Air-conditioning mode

In a general way, following points characterize the air-conditioning mode :

- With a setpoint at 24°C, the use of the hvac system is limited to the occupancy periods of each zone, so that zone temperatures of both buildings continue to fluctuate outside these periods. The separate conditioning of the zones appears clearly on the thermal behavior of the residential building, along with an electricity peak at 22h, when inhabitants move from living rooms to bed rooms. Such a zone distinction is not visible in the commercial building.
- Because of a more important air-conditioned surface in the commercial building (260 m^2 per floor), electricity peak for the hvac system is more than twice as important than for the residential building (80 / 96 m2 per floor).

Over the specific warm but not very hot week under consideration, the different configurations yield following results :

- As for all other configurations, the hvac electricity load of the reference case (Base) rises along with the ambient temperature, with peak loads for the residential / commercial building reaching up to 6.2 / 16.5 kW, and integrated consumptions of about 180 / 400 kWh.
- In absence of shading devices (NoShade), peak loads in the buildings are about 40 / 15% higher, and the hvac system is activated earlier in the week, resulting in about 50 / 30% higher electricity consumptions.
- With a building temperature during daytime that is kept lower than ambient, a tighter envelope (Tight) has a beneficial effect on the peak loads, with 7 / 29% savings. Not so on the integrated consumption though, at least for the residential building and on this particular week.
- To the contrary, direct ventilation (Dir) is particularly effective at night, resulting in 23% / 10% savings on the integrated consumptions, with almost no effect on the peak loads though.
- Same is true for buried pipes, which in simple as well as in alternate mode (Pipe and PipeDir) allow to maintain the buildings below the 24°C set point during the first part of the week, resulting in 35% to 50% savings on the integrated consumption. As the ventilation temperature however reaches that set point by the end of the week, these strategies have no effect on the peak loads anymore.
- To the contrary, phase-shifting can be maintained throughout this particular week, resulting in important 50 to 75% savings on the integrated consumption, as well as 15 to 40% savings on load peaks.

Finally, and quite differently from the free-floating mode, for which the building adapts to ambient conditions and benefits of inertial ventilation even over hot periods, the air-conditioning limits the use of inertial ventilation to periods where the ventilation temperature remains lower than the specified set point. No saving on the peak loads in hot periods is hence to be expected (Tab. 4).

Tab. 4 : Free-floating mode, average / maximum temperature during occupancy (white / grey), and air-conditioning mode, total / maximum electricity load of the hvac-system (white / grey).

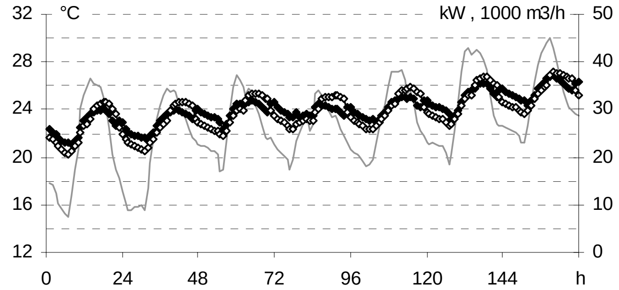
Config	**Warm week**								**Hot week**							
	Free-floating				**Air-conditioning**				**Free-floating**				**Air-conditioning**			
	Residential		Commercial		Residential		Commercial		Residential		Commercial		Residential		Commercial	
	°C	°C	°C	°C	kWh	kW	kWh	kW	°C	°C	°C	°C	kWh	kW	kWh	kW
Base	24.5	27.1	25.1	28.2	182	6.2	399	16.5	27.2	30.1	28.1	32.2	648	10.2	1138	27.6
	K	K	K	K	%	%	%	%	K	K	K	K	%	%	%	%
NoShade	+0.6	+0.4	+0.6	+0.8	+53	+39	+31	+16	+0.6	+0.4	+0.7	+1.0	+20	+40	+12	+2
Tight	+0.6	+0.0	+0.2	+0.2	+13	-7	-20	-29	+0.5	-0.3	+0.2	-0.1	-14	-4	-27	-24
Dir	-1.1	-0.3	-0.4	-0.3	-32	-5	-10	-4	-1.1	-0.2	-0.4	-0.2	-9	+0	-3	-0
Pipe	-1.1	-0.8	-1.4	-2.0	-35	-1	-36	+5	-0.8	-0.8	-1.1	-2.1	+7	+1	+7	+7
PipeDir	-1.6	-0.9	-1.5	-2.0	-49	-6	-41	+0	-1.2	-0.8	-1.2	-2.2	-5	-2	+3	+7
Shift	-1.1	-0.9	-2.2	-3.2	-53	-16	-71	-36	-0.8	-1.6	-1.9	-3.1	-10	-5	-6	-0
ShiftDir	-2.0	-1.6	-2.4	-3.2	-70	-29	-75	-39	-1.6	-1.7	-2.0	-3.2	-21	-11	-9	-0

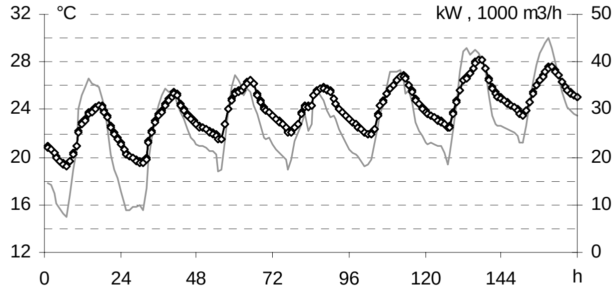
Warm week, ambient average / extreme : 22.7 / 30.0°C (Florianopolis, week no 52)
Hot week, ambient average / extreme : 25.8 / 34.3°C (Florianopolis, week no 4)

Free-floating / basic strategies

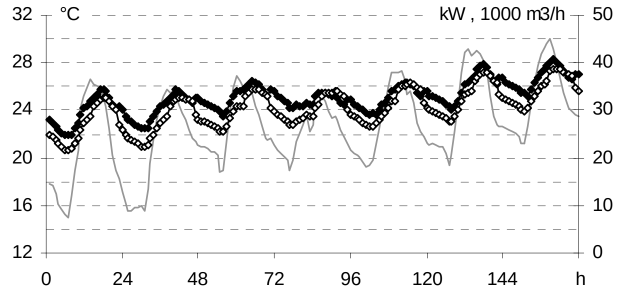
Residential **Commercial**

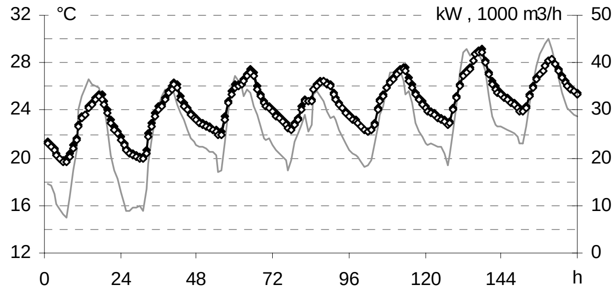
Base (infiltration only)



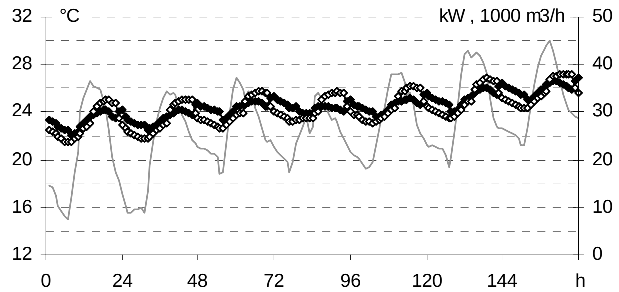


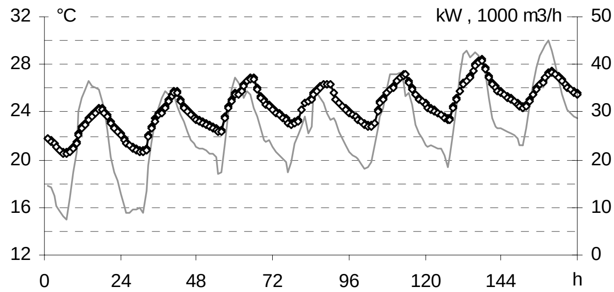
NoShade (no shading + infiltration only)



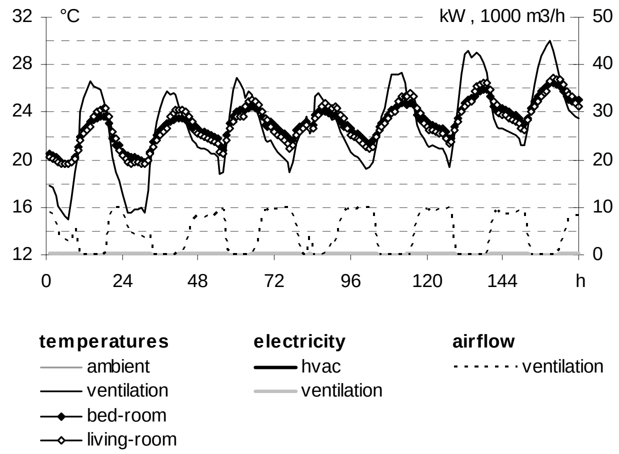


Tight (reduced infiltration)





Dir (direct ventilation)



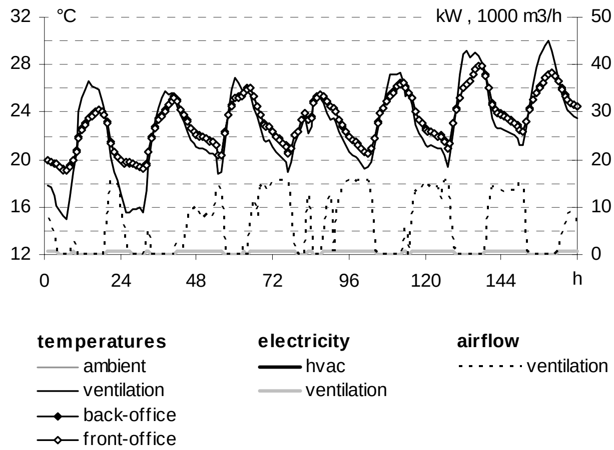
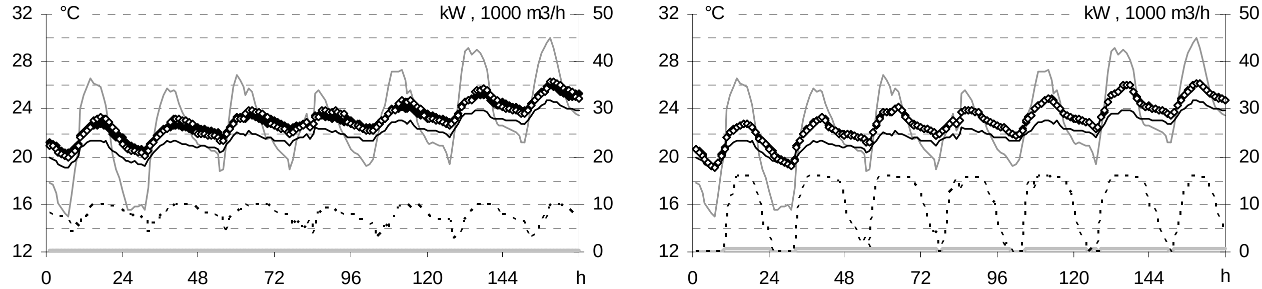


Fig. 8 : Free-floating / basic strategies : hourly dynamic (Florianopolis, week no 52).

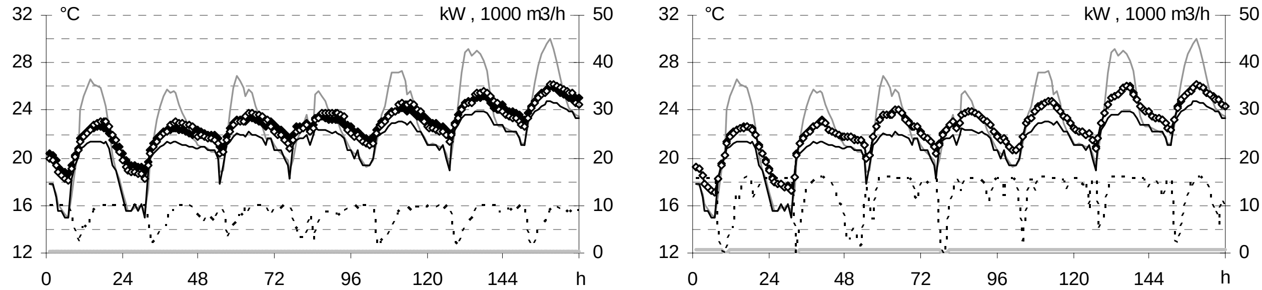
Free-floating / inertial ventilation

Residential | **Commercial**

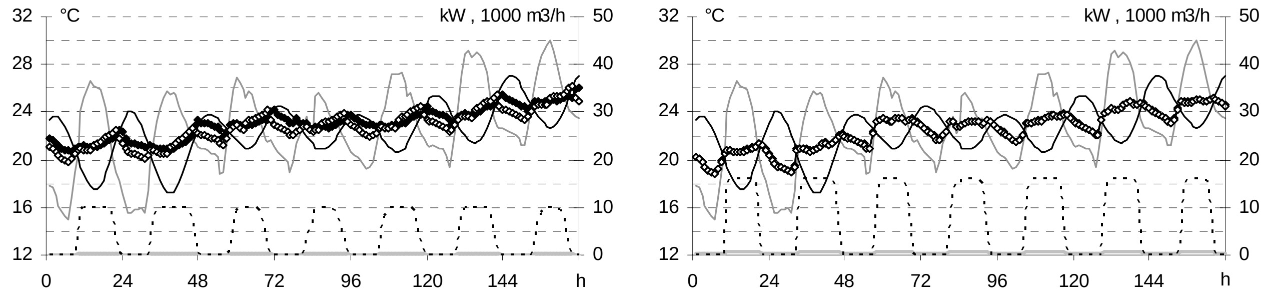
Pipe (buried pipes)



PipeDir (buried pipes + direct ventilation)



Shift (phase-shifter)



ShiftDir (phase-shifter + direct ventilation)

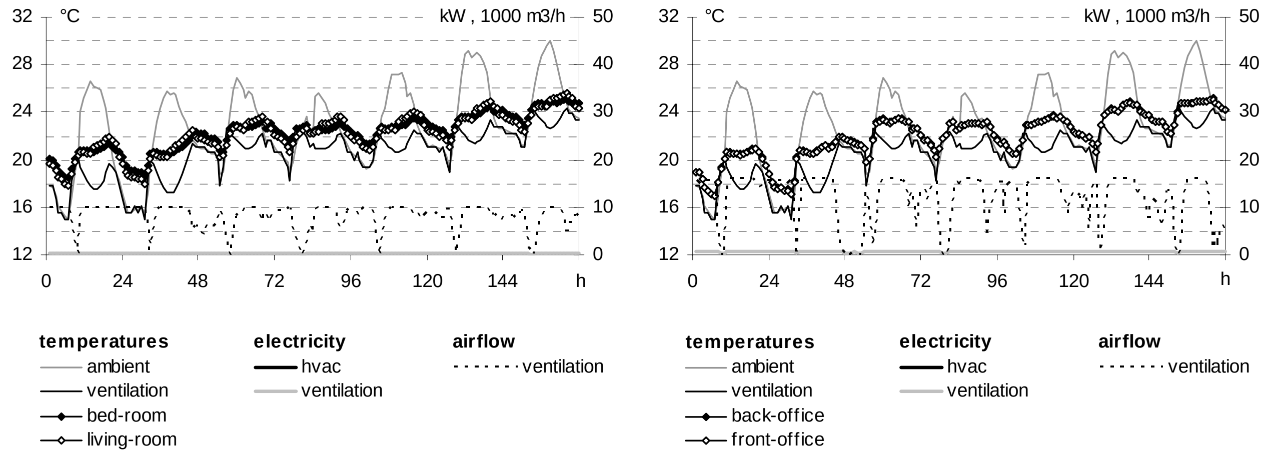
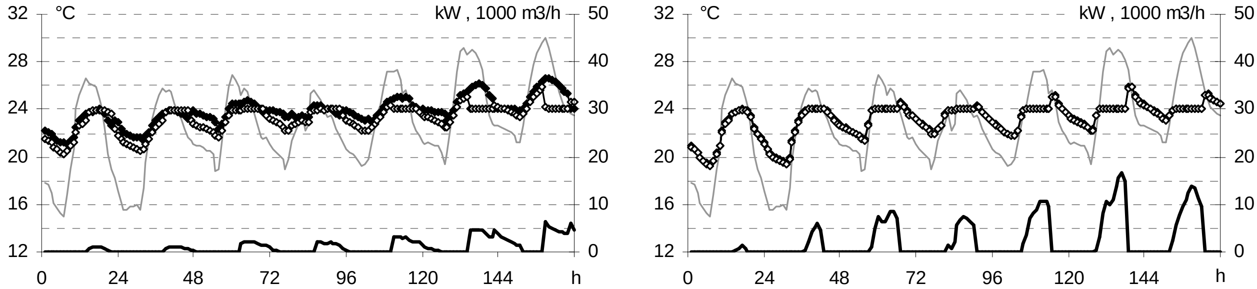


Fig. 9 : Free-floating / inertial ventilation : hourly dynamic (Florianopolis, week no 52).

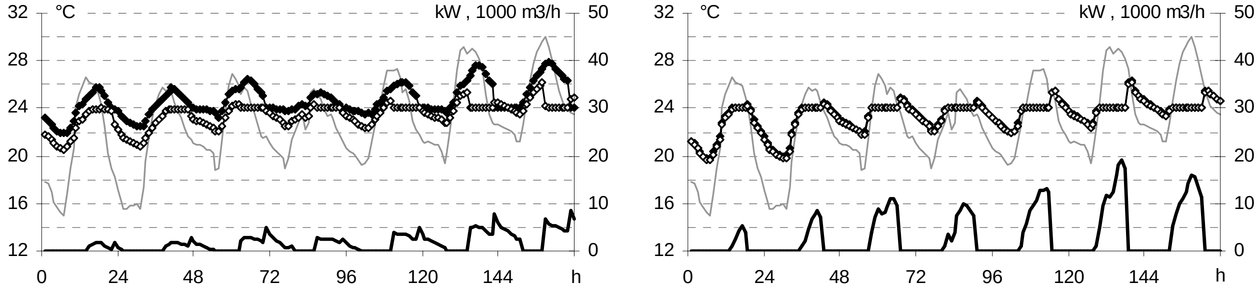
Air-conditioning / basic strategies

Residential **Commercial**

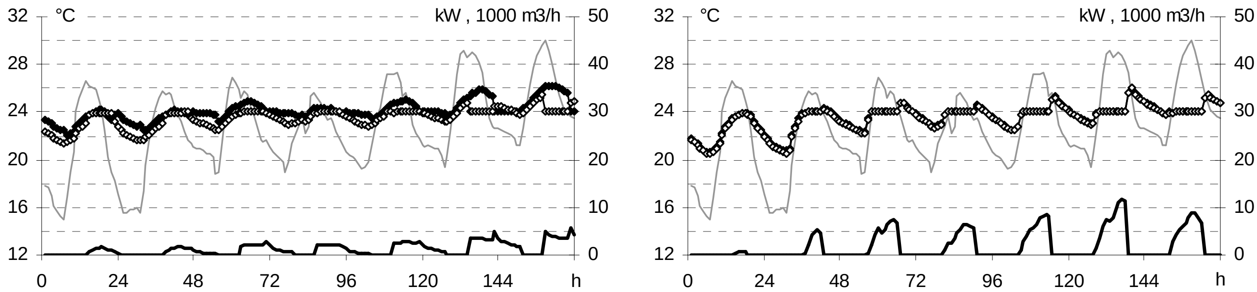
Base (infiltration only)



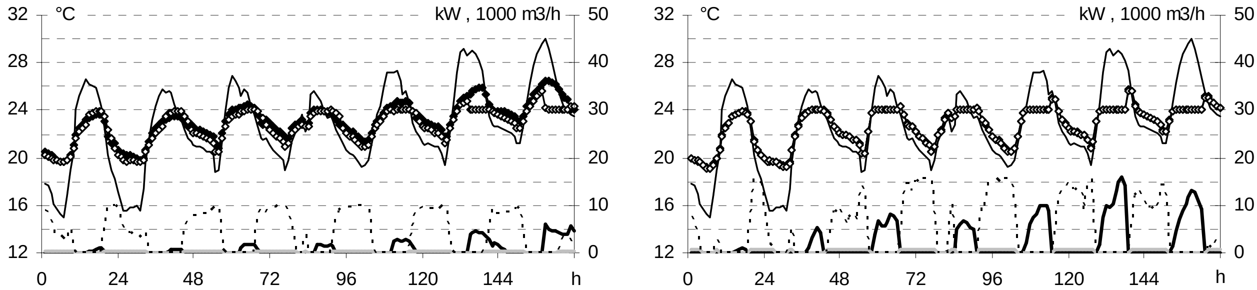
NoShade (no shading + infiltration only)



Tight (reduced infiltration)



Dir (direct ventilation)



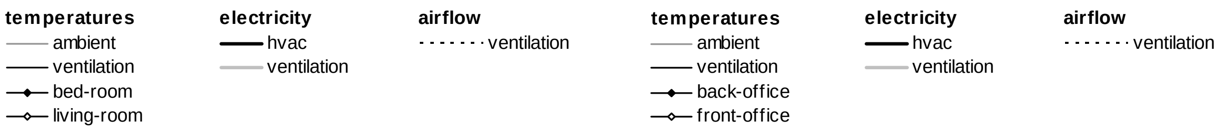
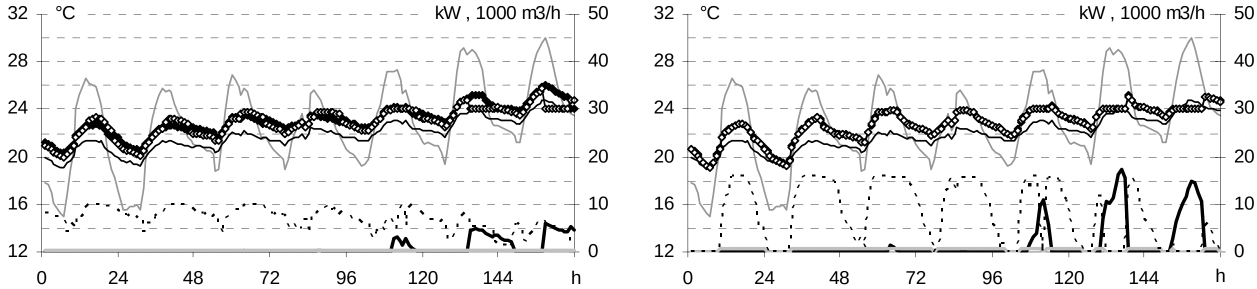


Fig. 10 : Air-conditioning / basic strategies : hourly dynamic (Florianopolis, week no 52).

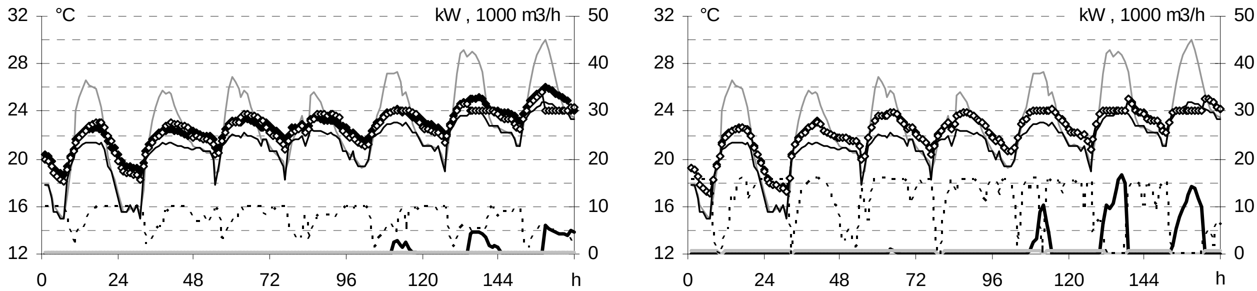
Air-conditioning / inertial ventilation

Residential **Commercial**

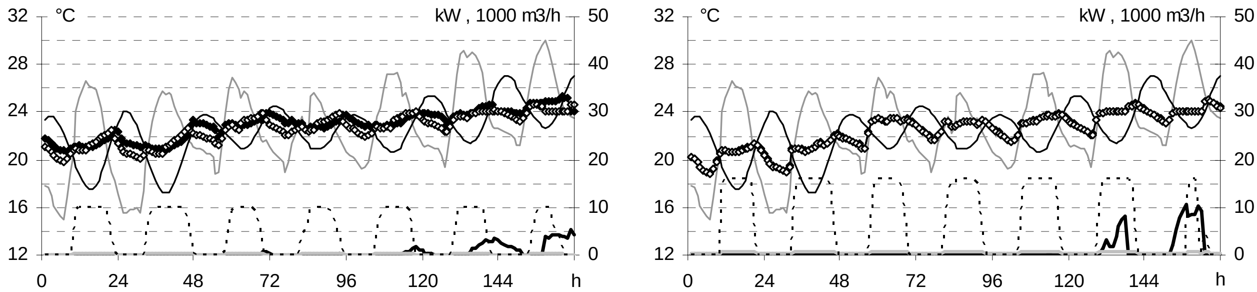
Pipe (buried pipes)



PipeDir (buried pipes + direct night ventilation)



Shift (phase-shifter)



ShiftDir (phase-shifter + direct ventilation)

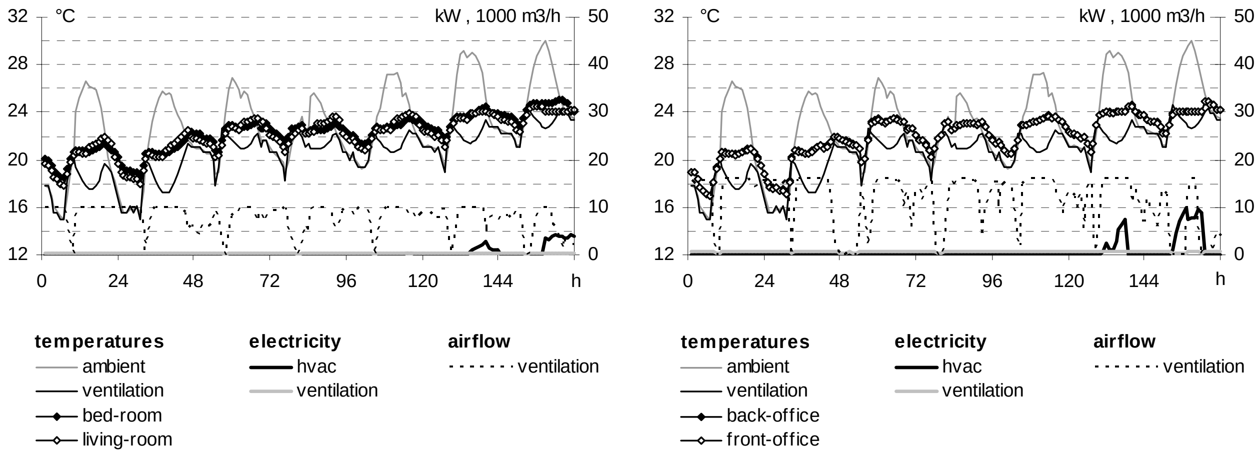


Fig. 11 : Air-conditioning / inertial ventilation : hourly dynamic (Florianopolis, week no 52).

6.2. Annual temperature overshoot and electricity consumption

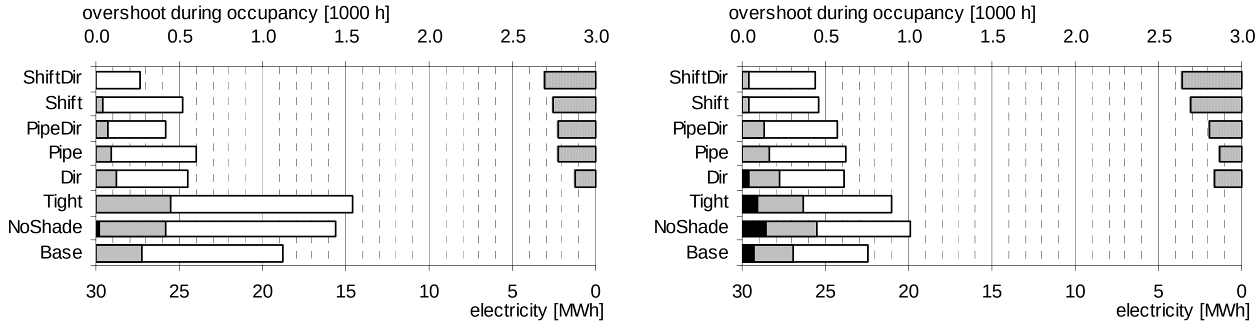
São Paulo

Conformingly with preceding analysis, the annually integrated values yield following results for the warm but not excessively hot climate of São Paulo (Fig. 12) :

São Paulo

Residential (6205 h occupancy) **Commercial (3650 h occupancy)**

Free-floating mode



Air-conditioning mode

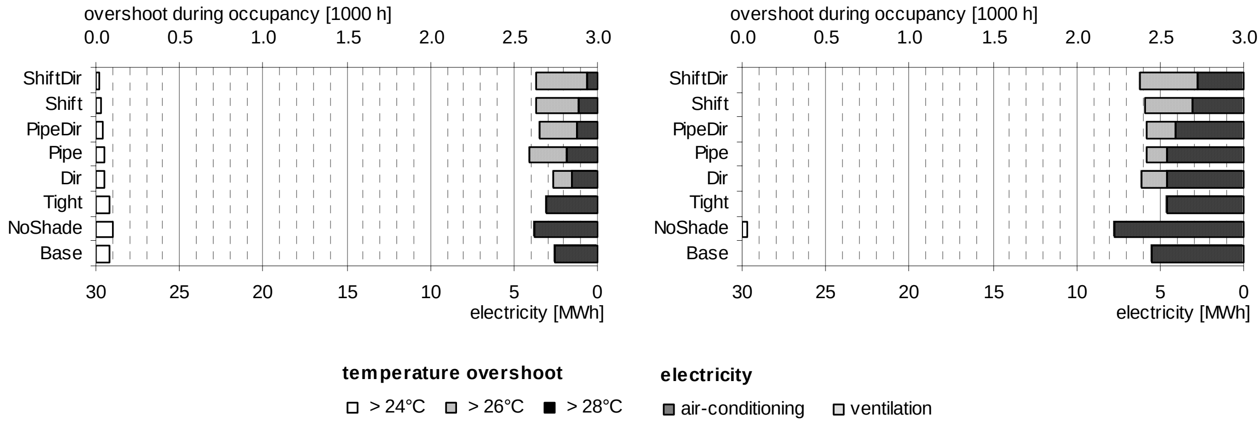


Fig. 12 : Annual temperature overshoot and electricity consumption, São Paulo (residential and commercial building, in free-floating and air-conditioning mode).

- In free-floating mode, a building with reasonable internal loads and correct solar protections may benefit from inertial ventilation, as well for afternoon/night occupancy (residential) as for a daytime occupancy (commercial). In the first case, inertial ventilation strategies allow to suppress more than half of the hours above 26°C, and just as much of the hours above 24°C. The effect is a little less important for day occupancy, although overshoots above 28°C are now completely suppressed.
- Globally, similar results are obtained with controlled direct ventilation from ambient, however with somewhat more overshoots in the 26-28°C range, as well as residual overshoots above 28°C in the case of diurnal occupancy.
- Electricity for ventilation however remains a key issue, with values close to that of an optimized hvac system, at least for residential buildings. Values presented here could be reduced by a factor 2/3, by activation of the ventilation system over the 6 warmest instead of 9 warmer months, but limitation of the charge losses in the distribution system remains a key factor, as pointed out before.
- For the same reason, inertial ventilation used as a back-up of air-conditioning is of little or no advantage, at least for a set point as low as 24°C. As a matter of fact, important savings in electricity consumption for the hvac system are compensated by additional electricity for ventilation, in particular

for its distribution in the building. This conclusion concerns an optimized hvac-system, with a COP of 3, and should again be balanced by the fact that the activation period of inertial ventilation could be reduced to the hottest 6 months only. As seen before, peak loads during the hottest days of the year will however remain unchanged.

- In any case, proper conception of the building envelope, in particular regarding solar protection, remains a preliminary measure to cooling techniques based on controlled ventilation.

Florianopolis

Similarly, the annually integrated values for Florianopolis are as follows (Fig. 13) :

Florianopolis

Residential (6205 h occupancy) **Commercial (3650 h occupancy)**

Free-floating mode

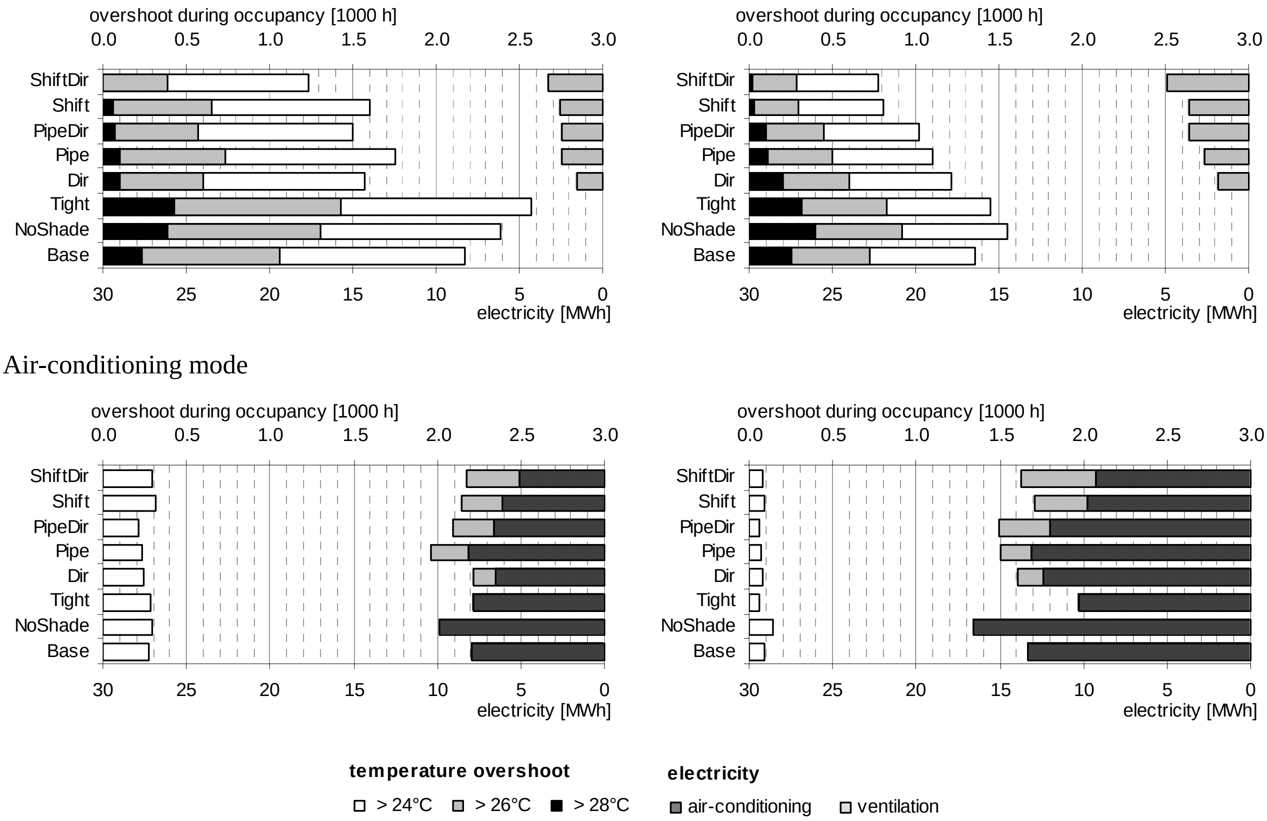


Fig. 13 : Annual temperature overshoot and electricity consumption, Florianopolis (residential and commercial building, in free-floating and air-conditioning mode).

- Again, proper conception of the building envelope, in particular regarding solar protection, remains a preliminary measure to any cooling technique based on controlled ventilation.
- In free-floating mode, because of a hotter summer, both free-floating buildings eventually rise above 28°C, even with the use of inertial ventilation (except for the case of phase-shifting used in combination with direct ventilation). Even so, inertial ventilation globally lowers the occurrence of the diverse overshoot levels. In the case of mixed day/night occupancy (residential building), the result however remains close to that of controlled direct ventilation, so that the clear advantage of inertial ventilation, in particular thermal phase-shifting, appears only for buildings with day-occupancy.

- Electricity for ventilation still remains a key issue, but is globally 2 to 3 times less than for an optimized hvac-system. Again, these values could be further reduced by activation of the ventilation system over the 6 warmest months only.
- Inertial ventilation used as a back-up of air-conditioning is now clearly of no advantage, neither in terms of peak loads nor of totalized electricity consumption.

7. CONCLUSIONS

Objective of this study was to evaluate the potential of two inertial ventilation techniques for passive cooling of buildings in Brazilian climates. Both of these techniques use inertia outside the proper building structure for active storage of the meteorological day/night temperature oscillation :

- Use of buried pipes, which consists in forcing ambient air through the soil, underneath or next to the building, so as to dampen the daily oscillation and to avoid temperature peaks during daytime.
- Thermal phase-shifting, a newly developed technique based on recent discovery of a simple physical phenomenon, which enables to delay the temperature peak over time almost without dampening, so that the cold temperature peak of the night be available in the middle of the day.

We did not consider the use of these techniques in annual mode (dampening / shifting of the annual temperature profile), which would imply much to large storage volumes for use in multi-floor buildings.

In a first step, the cooling potential of these techniques was characterized independently of any building dynamic, in terms of the available temperature differential relatively to a specified comfort set point :

- By dampening or differing of the oscillation peak, inertial ventilation enables for better distribution or shift of the cooling potential towards the diurnal periods, yielding an advantage for buildings which could not store the cooling potential of the night within their proper thermal mass.
- However, in hot climates like Rio de Janeiro and Recife one may not count with inertial ventilation for cooling below 26°C. Even with a set point at 28°C, cooling potential remains extremely low : during hottest months less than 30 K.h/day over day time (corresponding to less than 10 kWh/day per 1000 m3/h air).
- When averaged over the whole year, all other cities bear more reasonable but still limited values : for a set point at 28°C, depending on the ventilation strategy, 90 – 120 K.h/day over day time (30 – 40 kWh/day per 1000 m3/h air) and approximately twice as much over 24h. Furthermore, because of somewhat milder average temperatures, the yearly average cooling potential still exists for a set point at 24°C.
- The situation is somewhat different when evaluated over the hottest months only (January and February). Whereas the cooling potential persists almost unchanged for São Paulo and Brasilia, with 70 – 90 K.h/day, latter is not the case any more for Florianopolis and Porto Alegre, with 40 – 60 K.h/day, because of higher summer temperatures due to a stronger seasonal dynamic.

In a second step, the effective response of a residential as well as of a commercial building was evaluated in free-floating as well as in air-conditioning mode, with climatic data of São Paulo and Florianopolis. Conclusions as are follows :

- Proper conception of the building envelope, in particular regarding solar protection, in any case remains a preliminary measure to cooling techniques based on controlled ventilation.
- In a climate with important day/night oscillation, a free-floating building with reasonable internal loads and correct solar protections may benefit from inertial ventilation, with a reduction of the extreme building temperatures by 1 to 3 K, depending on the ventilation strategy.
- This lowers the occurrence of the diverse overshoot levels, as well for afternoon/night occupancy (residential) as for a daytime occupancy (commercial). Since these techniques are based on storage of the day/night temperature oscillation from ambient, they are however limited by the daily average

ambient temperature. During the hottest weeks, the building temperature hence still rises above 26°C, or even 28°C in the case of Florianopolis.

- The usefulness of these techniques obviously depends on the occupancy schedule, which further determines which one of the strategies is most adequate. In the case of a residential building, a comfort level similar to that of inertial ventilation is hence obtained with controlled direct ventilation from ambient. The clear advantage of inertial ventilation, in particular of thermal phase-shifting, hence only appears for buildings with day-occupancy.
- Electricity for ventilation however remains a key issue, with values close to that of an optimized hvac system, at least for a warm, but not too hot climate, like São Paulo. Further reduction of the electricity consumption should be achieved by activation of the ventilation system over the 6 warmest instead of 9 warmer months, but limitation of the charge losses in the distribution system remains a key factor anyhow.
- Quite differently from the free-floating mode, in which the building adapts to ambient conditions and benefits of inertial ventilation even over hot periods, the air-conditioning mode sets a limitation to periods where the inertial ventilation may be used as a back-up technology, so that no saving on the high peak loads in hot periods is to be expected, at least with a set point as low as 24°C.
- Important savings in annual electricity consumption may still be achieved for the hvac system, but they are compensated by additional electricity for ventilation, in particular for its distribution in the building. This last conclusion again should be balanced by the fact that the activation period of inertial ventilation could be reduced.

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REFERENCES

1. Hollmuller P. (2002) Utilisation des échangeurs air/sol pour le chauffage et le rafraîchissement des bâtiments : mesures in situ, modélisation analytique, simulation numérique et analyse systémique. Genève : Université de Genève, Faculté des Sciences (Thèse, Section de physique et Centre universitaire d'étude des problèmes de l'énergie).
2. Hollmuller P. (2003) Analytical characterisation of amplitude-dampening and phase-shifting in air/soil heat-exchangers. International Journal of Heat and Mass Transfer, vol. 46, p. 4303-4317.
3. Hollmuller P., Lachal B., Pahud D. (2005) Rafraîchissement par géocooling : bases pour un manuel de dimensionnement. Genève, CUEPE, Université de Genève. (Rapports de recherche du CUEPE n° 5).
4. Hollmuller P., Lachal B. (2005) Buried pipe systems with sensible and latent heat exchanges : validation of numerical simulation against analytical solution and long-term monitoring, in : Building Simulation, proceedings of the 9th International Building Performance Simulation Association, 15-18 August 2005, Montréal, Québec, École Polytechnique de Montréal, Vol.1, p. 411-418.
5. Hollmuller P., Lachal B., Zgraggen J.M. (2006) A new ventilation and thermal storage technique for passive cooling of buildings: thermal phase-shifting, in : PLEA 2006 - The 23rd Conference on Passive and Low Energy Architecture, 6-8 September 2006, Geneva, Switzerland, Université de Genève, Vol. 1, p. 541-546.
6. Labeee (2006), Arquivos Climáticos (www.labeee.ufsc.br/downloads/downloadaclim.html).
7. Tavares, S. F. (2003), Metodologia para análise energética do ciclo de vida de blocos cerâmicos vermelhos. Documento para qualificação (Doutorado em Engenharia Civil) – Programa de Pós-graduação em Engenharia Civil, Universidade Federal de Santa Catarina, Florianópolis, 2003.