Extensive sensitivity analysis of diverse ventilation cooling techniques for a typical administrative building in Mid-European climate

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346 - Extensive sensitivity analysis of diverse ventilation cooling techniques for a typical administrative building in Mid-European climate

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Abstract

Objective of this study is to compare the cooling potential of diverse passive cooling techniques linked to ventilation: controlled thermal phase-shifting (a recently discovered phenomenon), air-soil heat exchangers, evaporative cooling, and direct night cooling. The potential of these techniques is investigated for the case of an administrative building located in a moderate climate, with a specific attention to urban versus rural location, as well as normal versus extreme summer (of type 2003). Simulated building response is analyzed for a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains), in free floating mode as well as with auxiliary cooling backup.

Keywords: passive cooling, ventilation, building simulation.

1. Introduction

In most parts of Europe, electricity demand for air-conditioning is in rapid increase. Limitation of this demand requires as well adequate architectural and constructive measures (reduction off the solar and internal gains, access to the thermal mass), as development of passive techniques.

Subject of a recent discovery, controlled thermal phase-shifting of the day/night oscillation carried by an airflow is a promising phenomenon for cooling with very low electric consumption: by delaying the cool night peak by 8-12 hours, almost without dampening, latter becomes available in the middle of the day, when the demand for cold in the building is at its maximum.

In spite of its attractive temporal specificity, latter technique must be compared with other passive cooling techniques, in particular those which also make use the ventilation system (night ventilation, buried pipe systems, evaporative cooling). As for all of these techniques, the effective cooling potential further intrinsically relates to the building design and response.

Objective of this study is to clarify above mentioned points for the case of administrative buildings, located in moderated climates, as investigated here on base of a series of meteorological datasets for the Geneva region.

This paper resumes the findings of a research financed by the Swiss Department of Energy.

2. Meteorological data

A comparative analysis of summer meteorological data measured in the Geneva region over the 1990-2005 period yields following results [1], as illustrated in fig. 1:

- As well in urban as in rural areas, classified summer temperatures are very similar from one year to another, never exceeding 35°C. As a notable exception, 2003 however characterizes by around fifteen days with peak temperatures exceeding this threshold.
- Night temperature always drops lower in rural than in urban areas, whereas day temperatures do rise to similar peaks.
- To the contrary of the dry temperature, the wet bulb temperature of 2003 remains close to that of other years. This indicates a stable potential of evaporative cooling, to the contrary of direct night cooling and other techniques examined further down.

3. Building

Representative of the administrative building stock, the architectural typology is that of a low depth building, with 20 m^2 / 50 m^3 offices distributed on both sides of a broad central corridor. In terms of simulation, this typology results in a thermal model made up of three zones: two offices, on opposite facades and separated by the central corridor, with lateral boundary conditions given by identical interior climate (neighbor offices).

The parameters that govern the thermal behavior of the building are as follows:

- Thermal mass is mainly determined by 28 cm thick slabs, in heavy option (full concrete: 510 kJ/K.m^2) or medium option (combined wood structure with concrete filling: 350 kJ/K.m^2). In both cases, separation walls between offices add an additional 170 kJ/K.m^2 (relative to ground surface).
- Thermal insulation is any of low 1980's quality (6 cm, double glazing windows), or high quality as given by the Swiss Minergie standard (20 cm, triple glazing insulating windows).
- Solar access is determined by an E-W orientation on a low 5° horizon, along with a 50% window-to-wall ratio. Efficient external solar protection (overall g-value: 13% with 1980 windows, 7% with Minergie windows) are activated when direct radiation on the façade exceeds 10 W/m^2.
- Internal gains are 10, 20 or 35 W/m^2 (during occupation: 8-18 h).

4. Ventilation and passive cooling

4.1. Day/night storage systems

As an alternative or in conjunction with direct night ventilation, we will consider two types of passive cooling systems based on thermal storage of the meteorological day/night oscillation that is carried by ventilation (fig. 2):

- The so-called air-soil heat exchanger, in which the air passes through an array of pipes buried under or next to the building, for the meteorological day/night oscillation to be dampened by charge/discharge in the soil. The daily heat wave propagation extends on approximately 15-20 cm around the pipes, so that latter can be arranged in a compact geometry, with inter-axial distance of approximately 50 cm, immediately under the building, and if necessary in multi-layer.

  In the case of our study, we choose pipes with 12 cm diameter, for a specific flow of 100 m^3/h per pipe (2.5 m/s). With such a configuration 10 m of pipes make it possible to reduce the day/night amplitude to 41%, and 20 m of pipe to 17% (exponential damping), for a phase-shift which remains lower than an hour.

- The thermal phase-shifting device, in which the storage material is homogeneously distributed within the ventilating duct, in order to increase the heat-transfer surface and to decrease the penetration distance to thermal mass. Providing a homogeneous airflow and a good convective exchange, it then becomes possible to delay the day/night oscillation almost without dampening, for the night cooling peak to be available in the middle of the day.

  In the case of our study we choose a storage material consisting of 13/16 mm diameter PVC tubes that are filled with water, piled up perpendicular to the airflow, with a 2 mm spacing between tubes. With a duct cross-section of 50 x 50 cm subject to a specific flow of 100 m^3/h (0.39 m/s average interstitial velocity between tubes), the system enables an 8 h phase-shift with 1.6 m length, respectively a 12 h phase-shift with 2.4 m (linear phase-shifting), for a residual amplitude higher than 80%. This system hence not only differs from the buried pipes in terms of thermal behavior, but also in terms of an almost 10 times inferior storage volume.

First of these systems was subject of several case studies and theoretical analysis [2, 3], whereas second arises from a theoretical work that gave rise to recent lab developments [5]. They have both been object of theoretical developments, in particular in term of well validated analytical models [4, 5], which are used in this study.

4.2. Air flow and storage size

Just like for direct night ventilation, in which airflow may be increased at night to bring fresh air into the building, one can also consider preceding systems with airflows more important than the strict minimum air-change value, as long as the ventilation temperature is lower than the building.

Basing an occupation of 2 people per office, the base airflow during occupation is set at 72 m^3/h per office (1.3 ach), dropping at night to 6 m^3/h (0.1 ach).

As an alternative, we will also consider following 3 options of controlled flow:

- Same nominal flow (72 m^3/h), however also activated at night if the ventilation temperature is fresher than the building.
- Twice the base flow (144 m^3/h), activated according to the same thermal condition (else reduced to the base flow).
- Four times the base flow (288 m^3/h), activated according to the same thermal condition (else reduced to the base flow).

Such increased ventilation strategies imply adapting of the storage sizes, as well as adapted distribution systems (ducts and fans). They also imply electric overconsumption, which is to be kept as low as possible. While we will limit our study to the thermal contribution of these systems, we stress that the problem of electricity should eventually be studied carefully.

4.3. System integration and control

Since the investigated systems base on day/night charge/discharge, they must be irrigated 24/24 h. Control of the airflow injected into the building hence must take place by way of a valve at storage exit, with an upstream fan always running at nominal capacity.

At night, because of dampening or phase-shifting, temperature at storage output is warmer than ambient. Instead of single-mode operation, these storage devices may hence also be used in alternative mode with direct night cooling from ambient, with a control strategy injecting air into the building from which ever cooler source. Because of continuous irrigation of the thermal storage, such a strategy however requires a second fan for direct night ventilation.

We shall finally explore the potential of evaporative cooling, as a complement to inertial or direct ventilation. Latter potential will be examined for a constant 50% efficiency (humidification up to 50% of the potential given by the differential between dry and wet bulb temperatures).

Latter configurations will finally be evaluated both for the case of a free-floating building, as for backup by auxiliary cooling during occupation (26.5°C set-point).

5. Simulation

Simulation over the summer period (May-September) is carried out in two steps, with an automated overall approach:

- For each of the four meteorological data sets, the storage systems are pre-simulated for constant airflow, by way of specific analytical models developed previously [4, 5].
- Control of the systems, humidification and building response are then simulated within Trnsys.

6. Typical operation

Typical operation of some of the ventilation strategies is depicted here for a building with heavy thermal mass and high insulation, subject to 20 W/m^2 internal gains, in urban situation and for a normal summer of type 2004 (fig. 3). Analysis is given in terms of overheating duration (number of hours of occupation above 26.5°C), which should not exceed 100 h according to Swiss comfort regulation [6]:

- Limited to diurnal occupation, mere base ventilation (Base) yields a building response way above ambient. Overheating extends over more than 1000 h, of which 500 h above 30°C.
- With a twice more important airflow, limited to the fresh hours, direct night cooling (Direct) considerably reduces the diurnal building temperature. Overheating now reduces to 240 h, with a summer peak slightly below 30°C.
- By dampening of he day/night oscillation, buried pipes of 20 m length used in single-mode (Pipe20m-Sgl) allow for continuous over-ventilation of the building, whereas the 12 h phase-shifting device (Shift12h-Sgl) moves night ventilation onto the day period. Overheating now extends over 200 h, respectively 180 h, with a summer peak slightly below 29°C.
- Not depicted here, setup of these systems with alternative direct night cooling allows to reduce overheating below the 100 h limit.
- The strongest cooling potential however goes for evaporative cooling. Except for base ventilation, all the configurations with increased flow (direct ventilation, buried pipes, phase-shifting, in single or alternate mode) allow to remain below the 26.5°C threshold, hence largely respecting the Swiss comfort regulation.

7. Sensitivity analysis

An extensive sensitivity study explores the various possible configurations described further up (5760 combinations), as well as some alternatives with non-efficient solar protections. They are analyzed by way of classified illustrative tables (not presented here), in terms of overheating duration and peak temperature (free-floating case) as well as in terms of auxiliary thermal cooling energy and peak load (back up cooling at 26.5°C). Synthetic conclusions are as follows:

- It is shown once again that in terms of energy efficiency, good solar protections is the fundamental measure for reaching of acceptable summer comfort or for reducing of cooling energy. In comparison, all the other building parameters (thermal mass, insulation, orientation) are of secondary importance.
- That being, it is easier to obtain a good summer comfort with a well insulated building. In other words, and contrary to a hasty judgment, there is total compatibility between the winter and summer objectives. That is the case because for a comfortable administrative building, the internal temperature during occupation is lower than the outside temperature, the effect of insulation turning out to be positive. This can in principle be extended to residential buildings, insofar as when at night the differential is reversed, opening of the windows allows for adequate heat exchange.
- Internal loads also play a central role and have to be kept as low as possible. In this respect, the study on the other hand did not approach the effect of management by the occupants of opening, blinds, lighting and other apparatuses, management which was supposed to be correct.
- At climatic level, significantly different results are obtained for an urban or a rural site, or for a normal or an extreme summer (of type 2003).
- For a normal summer, a rural site, a building with efficient solar protection and modest internal loads (10 W/m^2), a good comfort can be guaranteed by simple night ventilation, with an air flow equivalent to the minimal hygienic rate (1.3 ach). In all the other cases, guaranteeing of the comfort (less than 100 h above 26.5°C) without auxiliary cooling is only possible with passively cooled air and higher ventilation rates.
- In this respect, evaporative cooling not only brings about the highest potential, but also the best stability in respect to summer conditions of type 2003. The effective water consumption for evaporation (in most cases less than 50 liter/m^2 per summer) remains sufficiently weak not to be a concern. Not tackled in this study, the question of hygiene and moisture however should be addressed carefully.
- As an upstream complement to evaporative cooling, but in some cases also as an alternative, day/night storage systems (buried pipes or phase-shifting) often make it possible to gain to gain 1-2 additional degrees on the peak summer temperature, respectively to harvest the few tens of hours of comfort that are missing, this even for an extreme summer. Such is particularly the case when these storage systems are set up in alternate mode with direct night ventilation.
- For an 8-18 h occupation, the storage system providing with the best result clearly is the 8 h phase-shifting device. That being, the choice between a buried pipe system or a phase-shifting device will also depend on other than thermal questions: available space, intervention possibilities, costs, maturity of technologies, electric consumption, etc.
- In all the cases, the question of increased airflow requires a detailed attention regarding charge losses and electric consumption, which was not tackled in this study. In this respect, air distribution in the building usually plays a more important role than the proper storage device.

- In the case of high internal gains (>30 W/m^2), auxiliary cooling turns out necessary. Implementation of above strategies then allows for considerable reduction in cooling energy, and to a lesser extent to peak power. In several cases the cooling system (especially distribution and emission) could be simpler and of less expensive than with traditional stand-alone air-conditioning, possibly allowing for moderate temperature sources, available in the environment (lake, ground).

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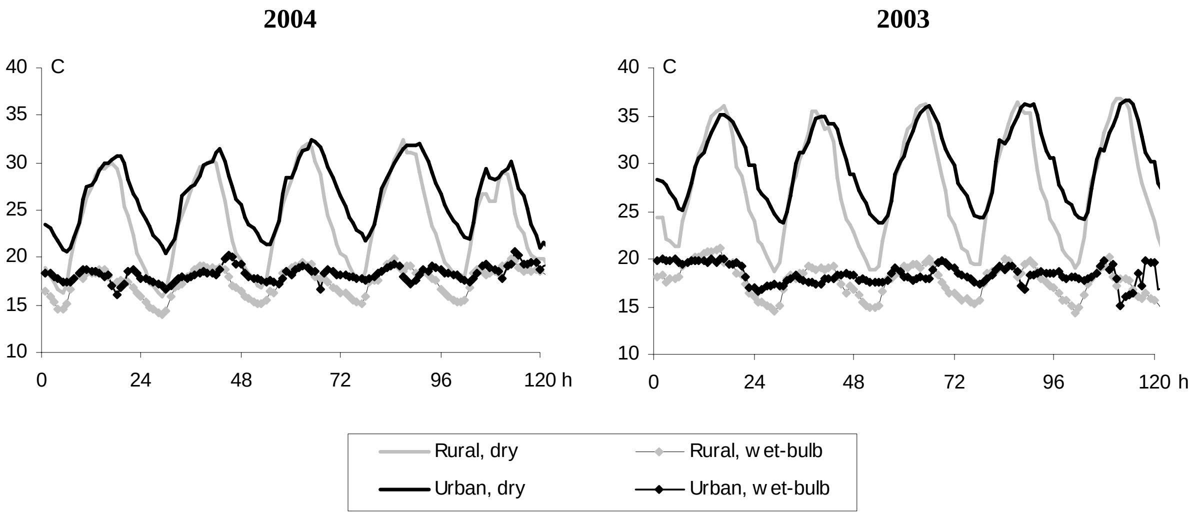

Fig. 1: Dry and wet bulb temperature, dynamic over a hot summer weak.

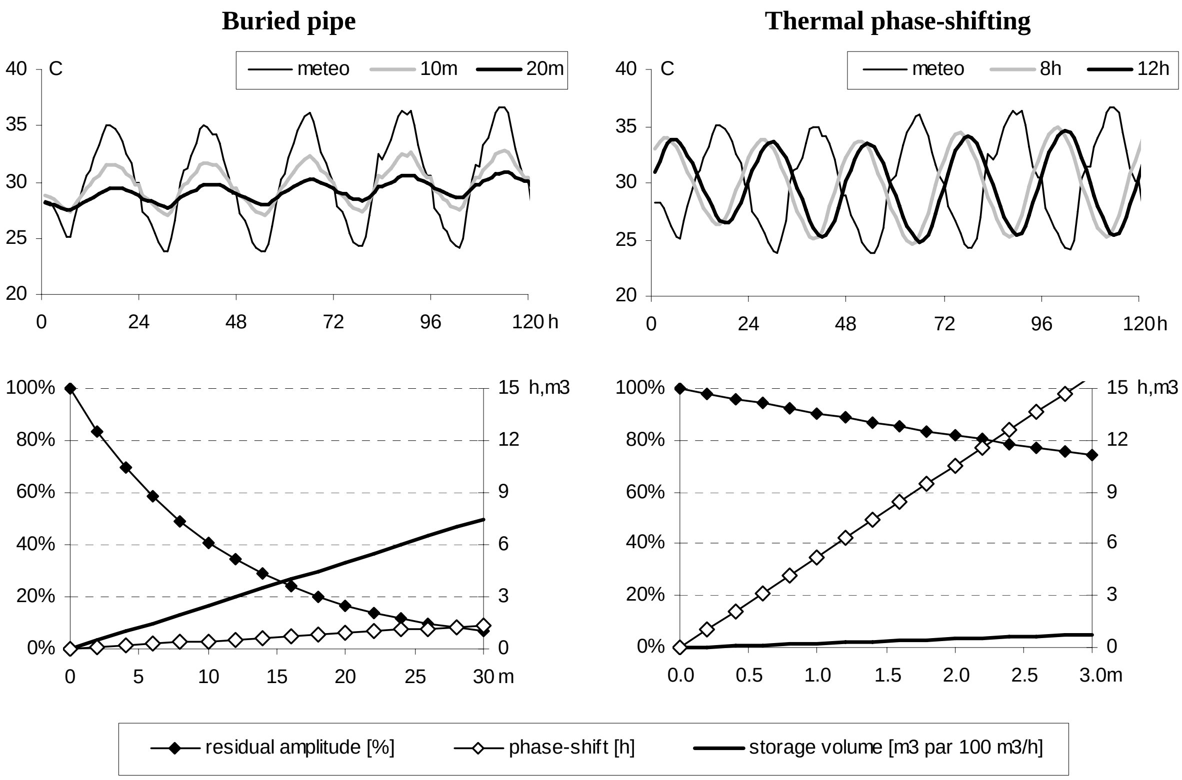

Fig. 2: Thermal storage, dynamic over a summer week (top) and dimensioning data (bottom).

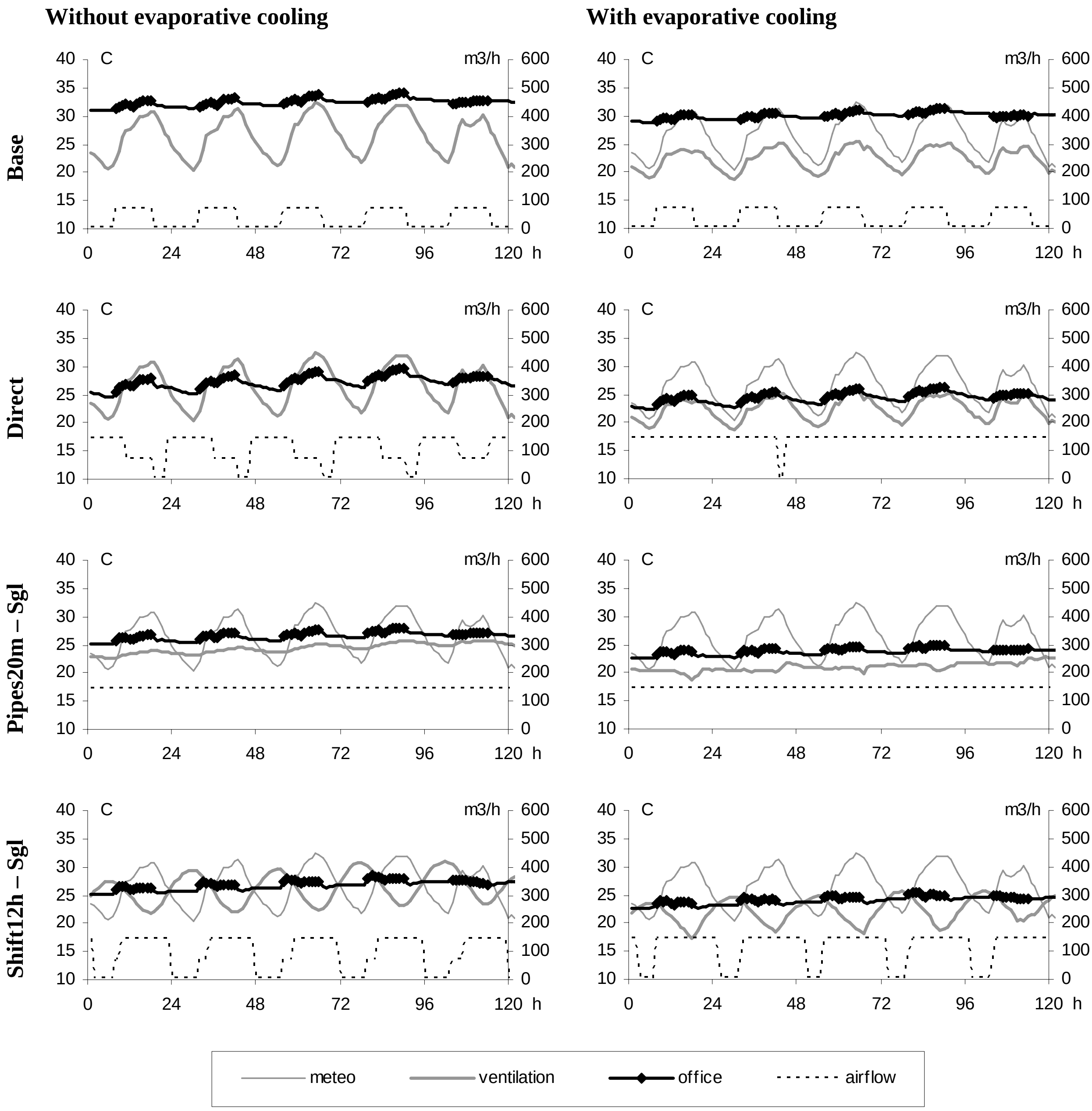

Fig. 3: Ventilation strategies and building response over a summer week (2004, urban situation).