A new ventilation and thermal storage technique for passive cooling of buildings: thermal phase-shifting

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ABSTRACT: This paper concerns a newly discovered passive cooling technique, which uses a packed-bed type of thermal storage so as to delay the meteorological oscillation carried by ventilation – almost without dampening it – thus enabling to restore the nightly cooling peak in the middle of the day. After description of the physical phenomena, by way of a simple analytical model, we present the development of a prototype for passive cooling in buildings.

Keywords: passive cooling, packed-bed, thermal storage

1. INTRODUCTION

The phenomenon we are interested in was first discovered by way of an analytical study on so called air/soil heat exchangers or buried pipe systems [1], which are usually set up for dampening of the daily or annual meteorological oscillation carried by a ventilation system. To the contrary of latter systems, it was theoretically and experimentally established, that it is possible to use piled up thin slabs so as to delay or phase-shift the input signal, almost without dampening it out. At that time the exact nature of the phenomenon however wasn't known by the authors, nor was the possibility of optimization by way of other geometries than the ones used for the first trials.

Because of their high exchange surface, so called packed beds, which are composed of solid particles and a fluid flowing in the interstitial space among them, have however been used for a long time in a variety of industrial processes, for thermal, mass or chemical transfers. Thermal applications, which are the ones we are interested in, have themselves led to a vast literature, of which an extensive review was done by Wakao and Kaguei [2]. An overview of this literature yet seems to show that the controlled phase-shifting effect put forward here had never been evidenced before.

The analytical models developed so far are almost always used in the case of a one-shot excitation (thermal storage within an initially static packed-bed, with incoming air at higher or lower constant temperature). That is the case in particular for one of the simplest of these models, the Schumann or two-phase model developed in 1929 [3], which usually serves as a reference for more elaborated models. As will be seen in this article, solution of the Schumann model in harmonic mode however yields a straight forward explanation of the controlled phase-shifting phenomena we are interested in, as well as a powerful tool for analysis of experimental results.

2. ANALYTICAL MODEL

2.1 System description

The physical phenomenon under consideration takes place in a thermal storage similar to a packed-bed (Fig. 1), submitted to an airflow with harmonic thermal input. The system is entirely defined by:

- A constant airflow m_a, the duct cross-section A and the void fraction η, which yield the free and interstitial velocities v_0 and v:

  $$v_0 = \frac{\dot{m}_a}{A\rho_a} \quad \text{and} \quad v = \frac{\dot{m}_a}{\eta A \rho_a} = \frac{v_0}{\eta}$$

  as well as the weighted air/packed-bed ratio of specific heat:

  $$\chi = \frac{\eta\, c_a \rho_a}{(1-\eta) c_s \rho_s}$$

- The storage length x, material volume V_s and exchange surface S_s, which relate as follows to the particle specific perimeter p_s and thickness r_s:

  $$p_s = \frac{S_s}{x}$$

  $$r_s = \frac{V_s}{S_s} = \frac{(1-\eta)A}{p_s}$$

  Note that latter characteristics need not refer to any specific particle geometry (spheres, slabs, etc.).

- The convective exchange h_0, which will be seen to strongly relate to the unitary periodic storage capacity k_0:

  $$k_0 = \omega c_s \rho_s r_s = \pi c_s \rho_s r_s \Big/ \frac{\tau}{2}$$

We will moreover retain following assumptions, which underlie the Schumann model:

- Particles are sufficiently small for their individual temperature to be regarded as homogeneous (no intra-particle temperature gradient).
- Repartition of particles and airflow on a cross-section is homogenous, and envelope is totally adiabatic (no transversal temperature gradient and no thermal losses).
- Axial diffusion between particles is negligible in comparison to convective heat exchange between air and particles.

Longitudinal cut of free and filled duct (left and right)

Zoom on a particle

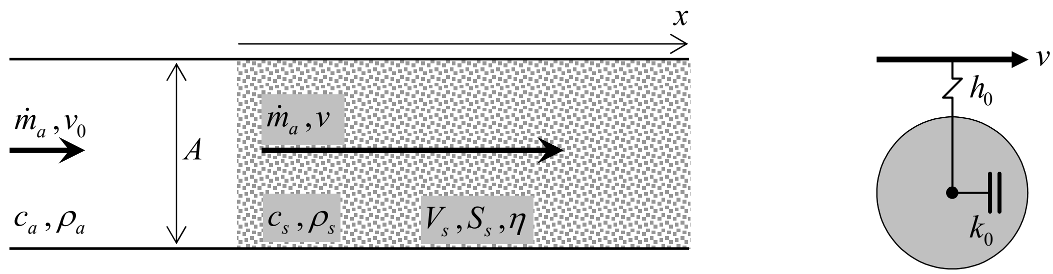

Figure 1: System schematic.

2.2 Schumann model

Foregoing assumptions lead to following two-phase model, which was initially proposed by Schumann [3] and is widely used as a reference for a “one-shot” excitation (thermal storage within an initially static packed-bed, with incoming air at constant temperature):

$$c_a \dot{m}_a \left(\frac{1}{v} \partial_t T_a + \partial_x T_a \right) + p_s h_0 \left(T_a - T_s \right) = 0$$

$$\frac{r_s}{2} c_s \rho_s \partial_t T_s + h_0 \left(T_s - T_a \right) = 0$$

However, as far as we know it has up to now never been solved or analyzed for the case of a harmonic excitation, as proposed here:

$$T_a \big|_{x=0} = \theta_0 \cos(\omega t)$$

2.3 Harmonic solution

In permanent regime, the solution accounts for a reduced as well as delayed signal:

$$T_a = \theta_0 \exp\left(- \frac{h p_s x}{c_a \dot{m}_a} \right) \cos\left(\omega \left(t - \frac{x}{v} \right) - \frac{k p_s x}{c_a \dot{m}_a} \right)$$

with:

$$h = \frac{h_0 k_0^2}{h_0^2 + k_0^2}$$

$$k = \frac{h_0^2 k_0}{h_0^2 + k_0^2}$$

2.4 Amplitude-transmission and phase-shift

By making use of the above parameter definitions, phase-shift and amplitude-transmission write as:

$$\varphi = \frac{k p_s x}{c_a \dot{m}_a} + \frac{\omega x}{v}$$

$$= \frac{k p_s x}{c_a \dot{m}_a} \left(1 + \chi \left(1 + k_0^2 / h_0^2 \right) \right)$$

$$\varepsilon = \exp\left(- \frac{h p_s x}{c_a \dot{m}_a} \right)$$

$$= \exp\left(- k_0 / h_0 \frac{\varphi}{1 + \chi \left(1 + k_0^2 / h_0^2 \right)} \right)$$

yielding following transmission and length for a complete phase-shift ($\varphi = \pi$):

$$\varepsilon_\pi = \exp\left(- k_0 / h_0 \frac{\pi}{1 + \chi \left(1 + k_0^2 / h_0^2 \right)} \right)$$

$$x_\pi = \frac{\chi \left(1 + k_0^2 / h_0^2 \right)}{1 + \chi \left(1 + k_0^2 / h_0^2 \right)} x_\eta$$

where:

$$x_0 = v_0 \frac{\tau}{2} \quad \text{and} \quad x_\eta = v \frac{\tau}{2} = \frac{x_0}{\eta}$$

2.5 Controlled thermal phase-shifting

By use of common storage material with high capacities as compared to air ($\chi << 1$) along with small enough particles as relating to the convective exchange ($k_0 << h_0$), preceding relations show the possibility to completely phase-shift the harmonic signal while barely reducing its amplitude:

$$\text{if} \quad \chi << 1 \text{ and } k_0 < h_0 \begin{cases} \varepsilon_\pi \approx \exp\left(-\dfrac{k_0}{h_0}\pi\right) \\ x_\pi \approx \chi\left(1+\dfrac{k_0^2}{h_0^2}\right)x_\eta \end{cases}$$

Controlled thermal phase-shifting hence merely appears as a reduction of the thermal wave-length x_η naturally carried by the airflow, by weighted heat storage between the air and the packed-bed. Not surprisingly, this interpretation corroborates the need of a good convective exchange and a small particle size (large exchange surface, small intra-particle gradient), so as to actually and efficiently distribute the heat wave between air and packed-bed.

Table 1 shows the theoretical length for complete phase-shifting of a daily or an annual thermal oscillation carried by an airflow with free velocity v_0 of 500 m^3/h per m^2 (0.14 m/s), for a packed-bed/air specific heat ratio $c_s\rho_s$ / $c_a\rho_a$ of 2000 and a perfect (infinite) convective exchange h_o.

Table 1: Length for total phase-shift (half a period), in function of void fraction, for perfect convective exchange.

η		10%	20%	30%	40%	50%	60%
v	m/s	1.39	0.69	0.46	0.35	0.28	0.28
$x_{\pi,24h}$	m	3.3	3.7	4.3	5.0	6.0	7.5
$x_{\pi,365\,day}$	km	1.2	1.4	1.6	1.8	2.2	2.7

Free air velocity v_0 : 500 m^3/h.m^2
Ratio of bed/air specific heat $c_s\rho_s$ / $c_a\rho_a$: 2000
Convective exchange h_o : infinite

From this table it is clear that although a seducing idea, phase-shifting of the annual oscillation turns out to be difficultly feasible, especially when taking into account the necessity of an adiabatic lateral envelope. From now on we will hence concentrate on the development of a prototype for phase-shifting of the daily oscillation, essentially for summer cooling of buildings in mild climates (diurnal temperature overshoots, with daily average within the comfort zone).

Perturbations

More elaborated models, on which detailed information can be found in the complete study [4], allow for characterization of perturbations which are not taken into account by the Schumann model. The most important result can be summarized in terms of the error yielded by the Schumann model for calculation of the amplitude-transmission at total phase-shift:

- Perturbation of intra-particle diffusion remains reasonable (less than 4% error) as long as the specific thickness r_s is less than 20% of the intra-particle penetration depth (which depends only on the signal frequency and the particle thermal diffusivity).
- Perturbation of axial or inter-particle diffusion remains reasonable (less than 5% error) as long as the related penetration depth is less than 5% of the length for complete phase-shift x_π.
- A non adiabatic envelope also contributes to dampening of the thermal wave, effect which is limited by a lateral insulation thicker or equal to the penetration depth proper to the thermal frequency and material (typically 15 cm for daily oscillation and common insulation materials). In that case, the perturbation on amplitude-transmission gets negligible (less than 1% error) when the exchange surface ratio between envelope and packed-bed is less than 1%.
- The potentially most important perturbation comes from a non homogenous airflow, due to non homogenous particle geometries or voids, which leads to mixing of non uniformly phase-shifted thermal waves, a phenomenon which may completely destroy amplitude-transmission of the input signal.

3. DEVELOPMENT OF PROTOTYPES

3.1 Description

The tested prototype consists of a 1 m long duct of 0.5 x 0.5 m cross section (0.82 x 0.31 m in the case of filling with ceramic balls, available in limited quantity), with 20 cm expanded polystyrene for lateral thermal isolation. Tested storage materials are as follows (Fig. 2):

- Gravel of different sizes (4/8, 8/16 or 16/32 mm, as well as a heterogeneous mix ranging between approximately 4 and 32 mm), filled up in a bulk; Measured properties: 2'620 kg/m^3, 0.86 kJ/K.kg; Void fraction: 0.35.
- Ceramic balls of 10 et 30 mm diameter, of manual cement, clay and lime fabric, filled up in a bulk (10 mm) or piled up regularly (30 cm); Measured properties: 2'150 kg/m^3, 1.10 kJ/K.kg; Void fraction: 0.39.
- Ceramic slabs of 15 x 31 cm basis and 2.5 cm thickness, piled up with 1 or 2 mm calibrated interstitial air gap; Measured properties: 1'820 kg/m^3, 1.05 kJ/K.kg; Void fraction: 0.04 or 0.07 for 1 or 2 mm air gap respectively.
- Perforated ceramic bricks of 25 x 6 cm basis and 12 cm height (in the direction of perforations), piled up horizontally so as to allow for the air to flow through perforations; Measured properties: 1'890 kg/m^3, 0.93 kJ/K.kg; Void fraction: 0.34.

Experiments had a duration of 5 days each (+ 2 initial days so as to establish a permanent regime), and were carried out with diverse airflows (between 10 and 1000 m^3/h par m^2). At input, thermally stable air from the lab was heated up so as to yield a superposition of 4 sinus of respectively 24, 12, 8 and 6 h period, for simultaneous calibration of the model upon several frequencies (Fig.3).

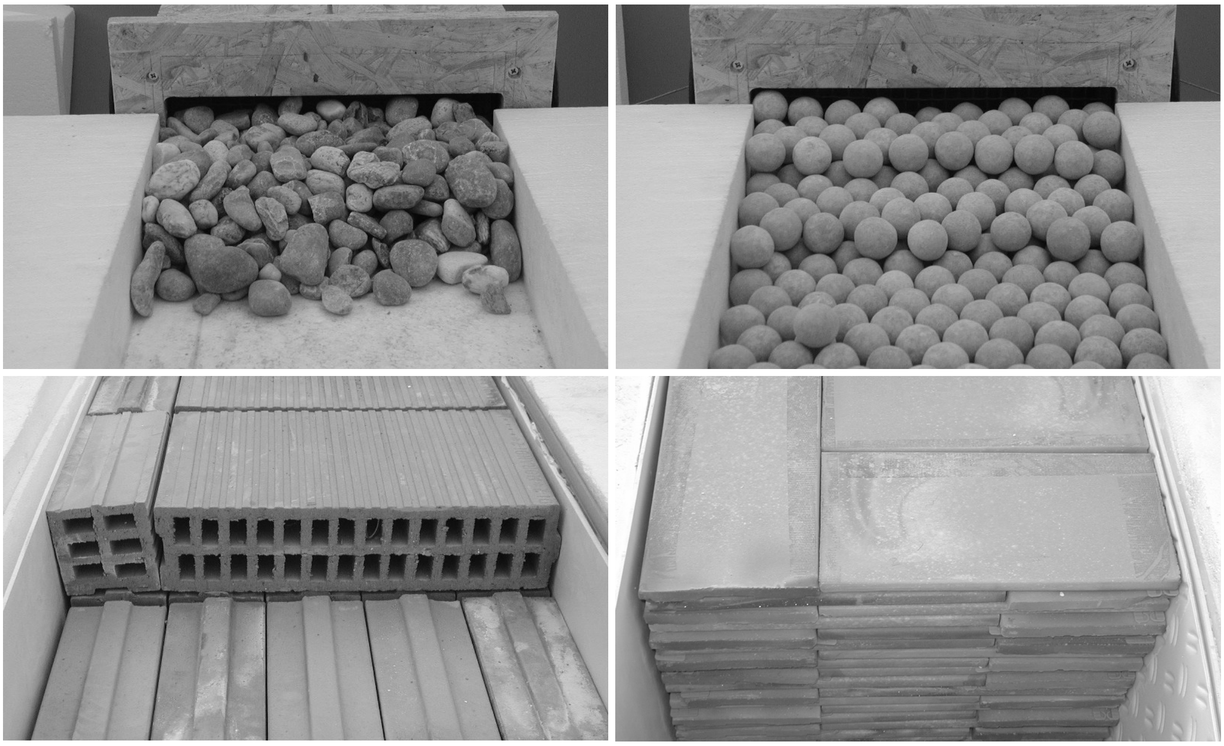

Figure 2: Prototype with different storage materials.

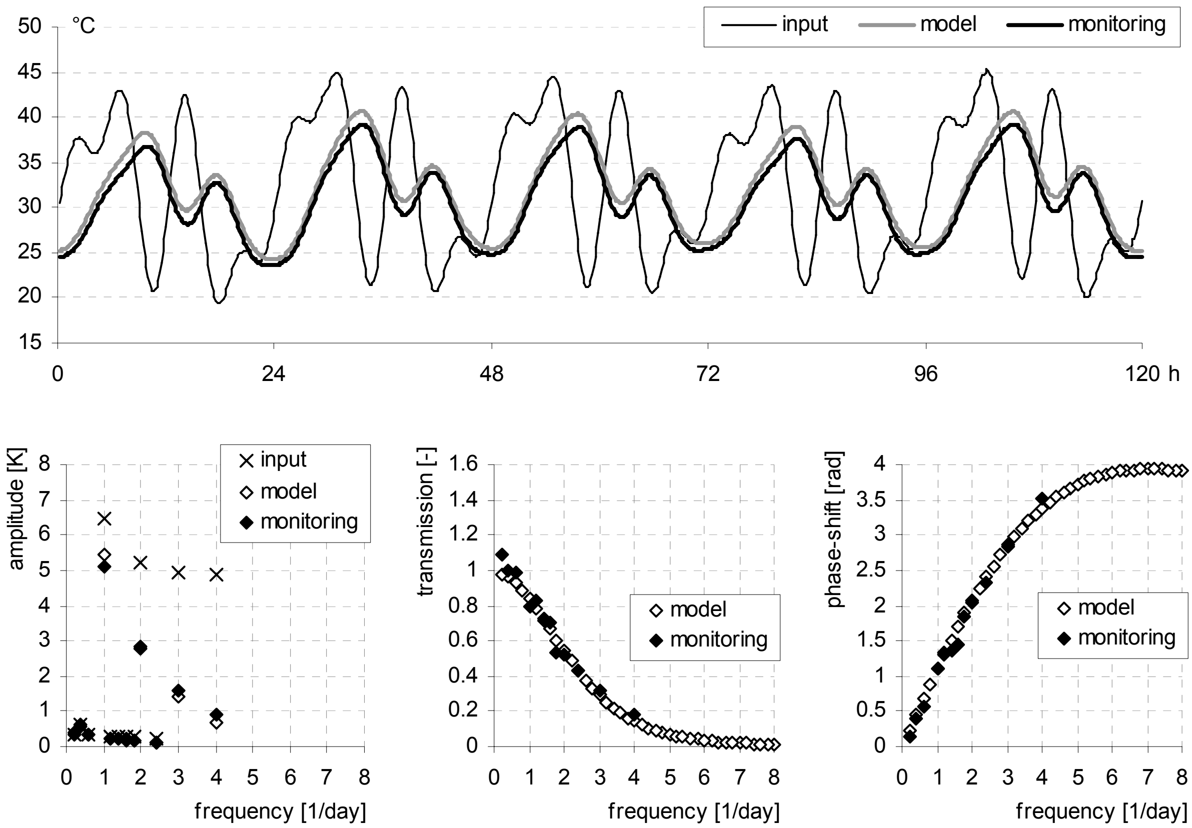

Figure 3: Typical monitored and simulated response to combined 4-sinus input (in this case: slabs with 2 mm gap, 95 m^3/h airflow): a) dynamic over 5 days; b) frequency response (amplitude-transmission and phase-shift) for frequencies with input amplitude above 0.2 K.

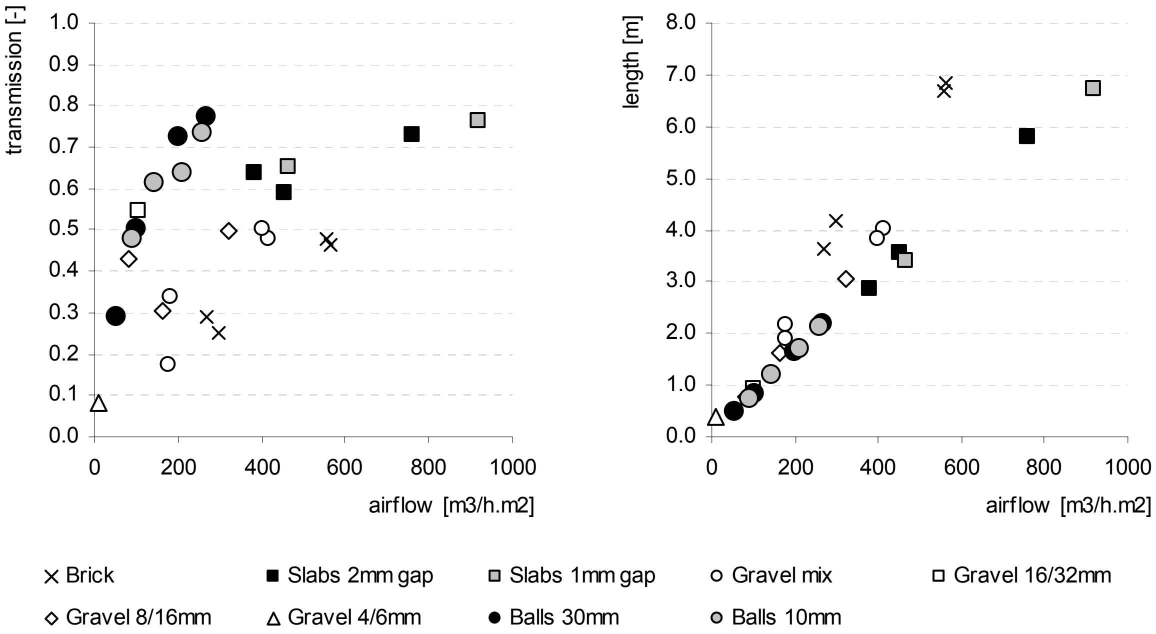

Figure 4: Extrapolated amplitude-transmission and system-length for complete 12h phase-shifting (adiabatic boundary conditions).

3.2 Analysis and results

Analysis of monitoring results is carried out in four steps (Fig. 3):

- Breakdown of the monitored input and output temperatures in complete Fourier series.
- For each frequency, computation of the Schumann model, taking into account thermal losses through the envelope (important in the case of ceramic balls, where the duct had a reduced cross section).
- Determination of effective airflow m_a and convective heat exchange h_0 by way of non linear optimization of the quadratic error between complete computed and monitored signal (sum of all frequencies).
- With the hereby calibrated model, suppression of the possible effect due to the envelope (adiabatic boundary conditions, corresponding to large enough duct section, yielding negligible boundary effects) and extrapolation to a length yielding the 12 h shift of the daily oscillation.

Use of this methodology on all experimental sets finally yields following results (Fig. 4):

- Conformingly with the model, the length (or volume) for a complete phase-shift rises linearly with the airflow, with an order of magnitude of 1 m^3 bed per 100 m^3/h air.
- Effective value of convective heat exchange h_o strongly depends on the air velocity, so that a decreasing airflow also implies a decreasing amplitude-transmission.
- In the case of the ceramic balls, transmissions over 70% are reached for an airflow of 200 m^3/h.m^2. If this material turns out to yield the best thermal results, it also is the most expensive one, at least in such small quantities (> 6'000 Euro/m^3).
- Use of a gravel bed certainly is the simplest and cheapest option (30 Euro/m^3), but reasonable results need a good granulometry control. If certain setups yield transmissions over 50%, other trials turn out very deceiving, probably due to non homogenous airflows. At this stage a certain doubt remains for use of such a material, and a more detailed study on air distribution in non regular geometries might be necessary.
- Transmissions over 70% are also reached with ceramic slabs, however for airflows of over 600 m^3/h.m^2 (over 4 m length). So as to grant for homogenous airflows, setup must however be realised carefully.
- Measured charge losses in all cases remain very low (around 50 Pa for a 12 h phase-shift), except for the slab geometry with a 1 mm gap (more than 100 Pa for a 12 h phase-shift).

So as to verify above extrapolation procedure, which bases on values from a 1m device, we finally tested a 3 m device (cross section: 0.5x 0.5 m) filled with thinner ceramic slabs (1.7 cm and 2 mm air gap):

- For 810 m^3/h.m^2 airflow, the 3 m device yields a 5.5 h delay and a 82% transmission (which extrapolates to 12 h and 65% for a 6.6 m device).
- For 560 m^3/h.m^2 airflow, the 3 m device yields a 8.0 h delay and a 61% transmission (which extrapolates to 12 h and 48% for a 4.5 m device.

Somehow lower values than before (Fig. 4) could be due to less regular slabs and slight air-tightness problems of the envelope.

4. SYSTEM INTEGRATION

Basing on last experimental setup, the validated model now allows for simulation of the system response for standard meteorological conditions during a summer week (Geneva, Switzerland), for cooling purposes of a building supposed to remain at 26 or 28°C. For the nightly cooling peak to be available twice a day, the 4.5 m cool-shifting device is supposed to be integrated into the ventilation system, in parallel to direct night ventilation (in which period the device continues to be ventilated for storage of the cooling peak, with warm output from day-time sent back to ambient).

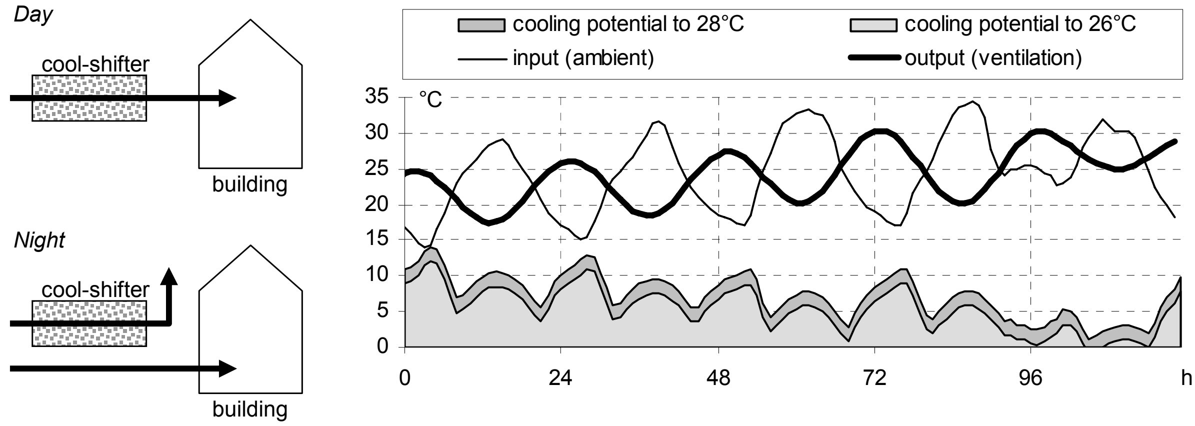

Figure 5: a) Integration into ventilation system and day/night ventilation strategy; b) input / output temperature profile over a summer week (Geneva) and associated cooling potential relatively to building set point of 26 or 28°C.

5. CONCLUSIONS

This study can be summarized with following conclusions:

- The possibility of complete phase-shift (half a period delay) of a thermal wave carried by an airflow, almost without dampening, was confirmed as well theoretically as experimentally. We did not found any trace of this phenomenon in literature.
- The most immediate application concerns phase-shifting of the meteorological day-night oscillation, for passive cooling of buildings during daytime. Although quite tempting, phase-shifting of the annual oscillation would require too important a storage volume for such a device to be viable.
- A theoretical analysis shows that thermal phase-shifting basically resumes to a simple phenomenon, the point being to use the thermal inertia of the packed bed so as to slow down the natural wavelength carried by the airflow velocity. This however requires a good convective exchange between air and storage material, as well as thin storage layers. Among the possible perturbations, intraparticle and axial diffusion as well as non-adiabatic boundary conditions are controllable. Potentially most striking problem could arise from an inhomogeneous airflow, which can induce important signal losses.
- On the experimental level, the development of lab prototypes confirms the possibility of complete phase-shifting of the 24 h oscillation, with an order of magnitude of 1 m^3 storage medium 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 inhomogeneous airflows, in relation with inhomogeneous storage geometries.
- Comparison between experimental and theoretical results is very satisfying and proves a high mastery of the implied phenomena. Although the question of inhomogeneous airflow remains somehow open, it should now be possible to realize functional real-size installations.

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REFERENCES

[1] 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, pp. 4303-4317.
[2] Wakao N. and Kagei S. (1982), Heat and mass transfer in packed beds. Gordon and Breach Science Publishers, p. 363.
[3] Schumann T.E.W. (1929), Heat transfer: a liquid flowing through a porous prism. J. Franklin Inst. 208, pp. 405–416.
[4] Hollmuller P., Lachal B., Zgraggen J.-M. (2004), Déphaseur thermique diffusif. CUEPE, Université de Genève, p. 98. (www.unige.ch/cuepe/html/biblio/detail.php?id=306)