SUMMER FREE COOLING VENTILATION POTENTIAL OF ROCK-BED HEAT STORAGE

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ABSTRACT

In many mild climates, during most part of summer, night-time temperatures are much lower than comfort temperatures. That is the case of most parts of Italy, where monthly mean temperatures in July and August are lower than 28°C. Nonetheless, daytime temperatures are higher, thus air-conditioning is widely used even in buildings with low inner gains, like dwellings.

It is obvious that it would be possible to have free cooling by storing night-time "cold" in order to provide it during daytime. On the other hand, as dwellings are usually occupied during nights, indoor temperature cannot be lowered as much as possible, without limiting comfort. So, rock-bed heat storage will let time shifting of temperature peak. Yet, even though it is not brand new, no design procedure is readily available. Moreover, the heat storage is very bulky so its integration in the architecture is a barrier.

Rock-bed heat storage is numerically simulated in order to figure out its actual behaviour and the relevance of geometrical parameters on its effectiveness. A Schumann two-phase model is used to simulate a free-cooling ventilation system with rock-bed heat storage for a new building, to be built in Pesaro, Italy.

Results show that for time shifting of temperature peak, heat storage volume is relevant rather than its length. This makes it possible to realize low energy demand ventilation systems by reducing pressure drop through the heat storage. Besides, when optimizing system use, its length becomes relevant again.

Keywords: heat storage, rock bed, ventilation, free cooling, dwellings

INTRODUCTION

During summer, in buildings without air conditioning systems, ventilation provides cooling, too. That is the case in many dwellings. Moreover, to accomplish the forthcoming Net Zero Energy Buildings limit, alternative passive cooling systems to traditional air-conditioning should be adopted. Actually, in many mild climates, mean daily outdoor air temperature are lower than comfort temperatures for people with low activity and summer clothes. According to [1], PMV would be lower than 0.5 as long as operating temperature will be lower than 28°C, for 1 met activity with 0.2 m/s air speed at 0.5 clo (common values for residential buildings). Thus, as long as mean daily outdoor air temperature is lower than 28°C, a proper ventilation with adequate heat storage is potentially able to provide cooling. This is close to ASHRAE-55 Standard comfort zone [2].

Much work is being done in the field of thermal energy storage for buildings and many review articles have been published on the subject, as recently reviewed by Heier et al. [3]. Most of the newly proposed techniques focus on the use of PCM either directly embedded in the building or in some system [4].

Moreover, mandatory insulation for envelope of new buildings makes heat transfer through it almost negligible. So cooling load in dwellings is usually low, being due only to internal gains, occupants' heat and solar radiation through windows. This makes it possible to control ambient temperature by ventilation with 2 h^{-1} air change rates.

The present study focuses on a new residential building currently at design stage, to be built in Pesaro, Italy. It is three levels high, 60 meters long, as sketched in Fig. 1. According to climate data, in July, that is the hottest month, the monthly mean daily average outdoor temperature is 23.2°C, even though the actual maximum temperature is 35°C. As stated above, cooling load is due only to: inner gains, that are evaluated to be 72 Wh/m^2 per day, occupants' heat, equal to 42 Wh/m^2 per day, and solar gain through windows (meanly $1m^2$ per 8 m^2 of floor area), that is equal to 458 Wh/m^2 per day in July. Thus, the daily cooling load is 212 Wh/m^3 per day. The daily cooling potential (DCP) per unit volume from ventilation, for a 2 h^{-1} air change, with 28°C ambient reference temperature, is calculated from typical mean year data by Meteonorm, assuming that ventilation will be off when outdoor temperature is higher than ambient reference temperature, as stated by eq. (1).

$$DCP = \int_{0am}^{12pm} n \cdot c_{p,a} \cdot \rho_a \cdot \max(T_r - T_o, 0) \cdot d\tau \qquad (1)$$

where n is air change rate, c_p is specific heat, ρ is density, T is temperature and τ is time, while subscript a is for air, r is for room and o is for outdoor.

DCP is always higher than daily cooling load per unit volume. Thus, ventilation could be adequate for temperature control. Nonetheless, eq. (1) slightly overestimates cooling energy as no lower limitation is set to inlet air temperature.

In order to level inlet temperature, a heat storage could be used. The simplest system is a rock-bed heat storage with one-way continuous ventilation. It could be set in a specifically dedicated basement. Similar systems has been proposed and used in the last decades, but no design tool is readily available in the open literature. Currently, such systems are yet to be investigated, as reported by Brun et al. [5].

In this framework, the present paper aims to study the relevance of the main rock-bed parameters on its performance. Different mass flow rate per unit cross area are evaluated from 0.25 $kg/s \cdot m^2$ to 2 $kg/s \cdot m^2$, and different rock-bed lengths from 5 m to 60 m.

METHOD

The two-phase Schumann's model [6] is used for the rock-bed heat storage. The assumptions of the model are:

- temperature in each storage element T_b is homogeneous and independent of cross-section;
- the arrangement of the rocks is independent of cross section and along the length of the system so that air flow and heat transfer coefficient are homogeneous, too;
- axial heat transfer is negligible as well as through rock-bed envelope.

Figure 1: Sketch of reference building.

Imposing that heat transfer rate of rock phase is equal to air phase, eqs. (2-3) are given:

$$\frac{\partial T_b}{\partial \tau}=\frac{h_v}{(1-\varepsilon)\cdot\rho_b\cdot c_{p,b}}\left(T_a-T_b\right) \tag{2}$$

$$\frac{\partial T_a}{\partial x}=-\frac{h_v}{G\cdot c_{p,a}}\left(T_a-T_b\right) \tag{3}$$

where ε is void fraction, G is mass flow rate per unit cross area, x is abscissa along the rock-bed, subscript b is for rocks, and all other symbols are as stated above. h_v is convection heat transfer coefficient per unit volume given by eq. (4) by Löf and Hawley [7], in which d is rock equivalent diameter:

$$h_v=651.7\cdot\left(\frac{G}{d}\right)^{0.7} \tag{4}$$

Equations (2-3) are solved through a control-volume formulation of the finite-difference method. An explicit forward scheme is used for time stepping. The linear equations are readily solved using short enough time step and axial mesh through a specific code in Matlab.

The code is validated against the analytical solution given in [5] with very good agreement with 60 seconds time steps and uniform 0.1 m mesh.

RESULTS AND DISCUSSION

Numerical simulations have been performed for different lengths and mass flow rate per unit cross area in the above stated ranges. 2400 kg/m^3 rock density, 40% void fraction, 5 cm rock equivalent diameter, and 1 kJ/kg·K specific heat of both rock and air has been assumed.

The outlet temperature for two values of mass flow rate and three lengths of rock-bed are plotted in Figs. 2 and 3 together with outdoor air temperature. In the first figure, related to 0.25 kg/s·m^2 time shift between outdoor air temperature peak and rock-bed outflow temperature peak is some hours for 5 m long system, while it is more than a full day for 20 m long and about 4 days for 60 m long rock-bed. On the other hand, in Fig. 3, where temperature values for systems of same length with a four times higher flow rate per unit cross section are plotted, just the 60 m long rock-bed reaches a full day time-shift.

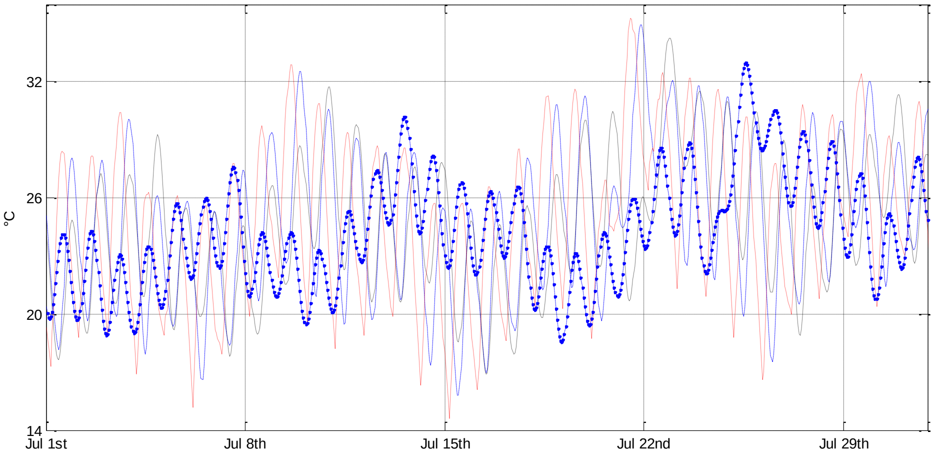

Figure 2: Outflow air temperature with 0.25 kg/s·m^2 for 5 m (blue long-dash), 20 m (black short-dash) and 60 m (blue dot-dash) long rock-bed heat storage and outdoor air temperature (red continuous).

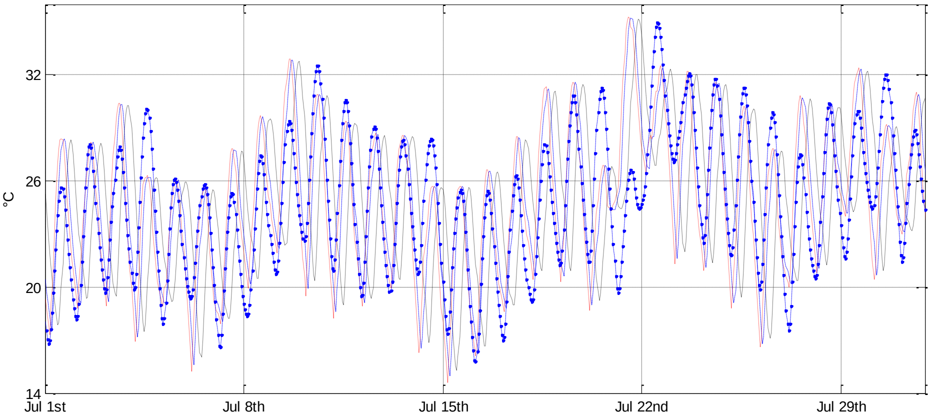

Figure 3: Outflow air temperature with 1 kg/s·m^2 for 5 m (blue long-dash), 20 m (black short-dash) and 60 m (blue dot-dash) long rock-bed heat storage and outdoor air temperature (red continuous).

Actually, at a given flow rate, heat storage volume is proportional to the ratio of system length to its flow rate per unit cross area. Thus, the systems in Fig. 2 have four times the heat storage mass of systems in Fig. 3 with same lengths. Similar plots are provided in Fig. 4 for 10 m^3/(kg/s) heat storage realized with 5 m, 10 m, 20 m and 40 m long rock-bed. It is clearly seen that temperature response of these systems on a 24 hours solicitation is related uniquely to storage mass. Time-shift of temperature peak for all calculated systems has been graphically evaluated and plotted against volume per flow rate, as depicted in Fig. 5, showing a linear correlation, given by eq. (5).

$$Time-shift = 0.4052 \times \mathrm{v}\ [h] \tag{5}$$

To evaluate energy performance of systems, for each bed length and each mass flow rate the daily cooling potential with thermal storage (SCP) have been calculated, using eq. (1) with rock-bed outlet air temperature (T_f) instead of outdoor air and 28°C as room air temperature. Then the ratio of SCP to DCP for each day has been calculated. During summer, outdoor air is often lower than reference temperature, thus, actual hot days has been found in order to make comparisons on actual cooling periods. Therefore, hot days are defined as those days in which outdoor air temperature exceeds reference temperature even for just an hour. The overall effectiveness (Φ) of the heat storage for free cooling is thus the sum of the ratio for each day, divided by the number of hot days, and could be directly found by eq. (6).

$$\Phi = \frac{1}{N_{hotdays}} \sum_{hotdays} \frac{SCP}{DCP} = \frac{1}{N_{hotdays}} \sum_{hotdays} \frac{\int_{0am}^{12pm} \max(T_r - T_f, 0) \cdot d\tau}{\int_{0am}^{12pm} \max(T_r - T_o, 0) \cdot d\tau} \tag{6}$$

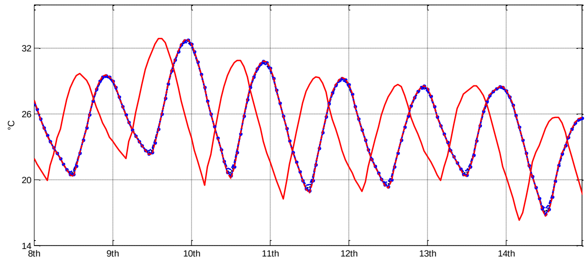

Figure 4: Outflow air temperature with 10 m^3/(kg/s) for 5 m (blue long-dash) and 20 m (blue dot-dash) long rock-bed heat storage and outdoor air temperature (red continuous).

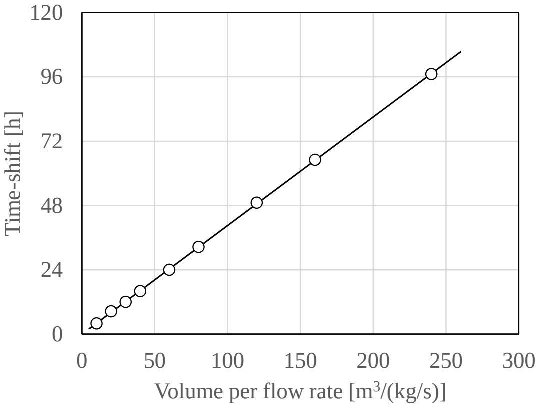

Figure 5: Time-shift of temperature peak vs. System volume per mass flow rate.

Plotting system effectiveness versus system volume per unit mass flow rate shows again a straight correlation, as reported in Fig. 6.

The above stated effectiveness implicitly presumes that ambient supply air will be provided only from the heat storage, that is: ambient cooling will be available only when rock-bed outflow temperature is lower than reference temperature. As the main effect of thermal storage is time shifting of outdoor temperature wave, there will be many periods in which outflow temperature is higher than outdoor temperature. As shown by Brun et al. [5], optimization of heat storage systems for free cooling may provide a significant improvement in its effectiveness. The simplest improvement could be provided presuming that air flow in the heat storage is constant, while ambient ventilation could be provided either by rock-bed outflow or by outdoor air directly, whichever is lower. Therefore, an optimized effectiveness (Φ_o) may be defined as in eq. (7):

$$\Phi_O = \frac{1}{N_{hotdays}} \sum_{hotdays} \frac{\int_{0am}^{12pm} \max(T_r - T_f, T_r - T_o, 0) \cdot d\tau}{\int_{0am}^{12pm} \max(T_r - T_o, 0) \cdot d\tau} \qquad (7)$$

Plotting system “optimized effectiveness” versus system volume per unit mass flow rate, as reported in Fig. 7, shows that system length becomes relevant for high heat capacity storage systems but in a non linear way, as 40 m long system performs better than both 60 m and 20 m systems.

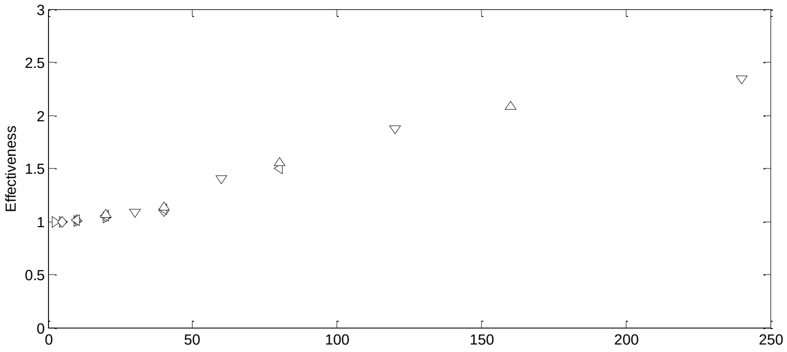

Figure 6: System effectiveness versus system volume per unit mass flow rate.

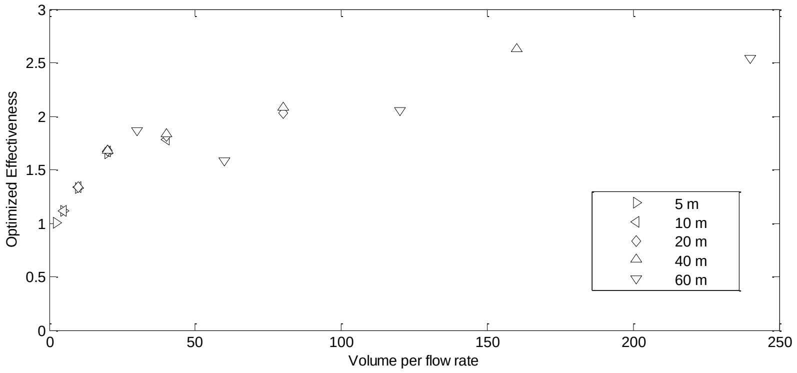

Figure 7: System "optimized effectiveness" versus system volume per unit mass flow rate.

CONCLUSION

The two-phase model of rock-bed heat storage has been numerically solved for dwelling ventilation with typical mean year data for Pesaro, Italy. Results show that such systems could be sufficient for cooling in low inner gain buildings like residential ones.

Time-shift of temperature peak is related to heat storage volume per unit mass flow rate and the correlating equation is given. In order to provide a time-shift of 12 hours (that is night-day temperature inversion of supply air for ventilation), 30 m^3 systems per unit mass flow rate would be needed with set parameters. Even though these results has been figured out from a specific climate, they are properly applicable to almost any other climate as they depend only on main solicitation period, that is always 24 hours.

The system will be effective in increasing daily cooling potential of outdoor air. When optimizing free cooling, system length becomes relevant. As system length is straight correlated to energy demand of fan, optimizing the system requires further research.

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