*Article*

# A First Approach to Natural Thermoventilation of Residential Buildings through Ventilation Chimneys Supplied by Solar Ponds

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**Abstract:** The exploitation of natural ventilation is a good solution to improve buildings from an energetic point of view and to fulfill the requirements demanded by the thermohygrometric comfort and the air quality in enclosed spaces. Some past researches demonstrated how some devices, useful to this purpose, follow the principles of solar chimneys and are able to move air masses while exploiting the Archimedes thrust. The natural ventilation must be supplied by a flow moving upward, generated by a heat source performing at temperatures slightly higher than the one present in the environment. To have a minimum energetic effect, the heat can be extracted from solar ponds; solar ponds are able to collect and store solar energy in the geographical regions characterized by sufficient values of solar radiation. Thus it is possible, in summer, to provoke a nocturnal natural ventilation useful for the air change in indoor spaces (in those climatic areas where, during the night, there is a temperature gradient).

**Keywords:** natural ventilation; solar chimney; solar pond; free cooling; Nearly Zero Energy Building

## 1. Introduction

Nowadays, everyone is aware that the main priority during the planning of buildings is the building-plant system energy quality. The European Directive EPBD 2 (Energy Performance of Building Directive) 2010/31/UE states that all those buildings constructed after 2020 must be Nearly Zero Energy Buildings (nZEB) [1]. A nearly zero-energy building presents high energy performances (almost self-sufficient) and the resulting reduction of energy requirements is fulfilled almost entirely by energy supplied by renewable sources generated in areas inside the system [2–4].

This is why the construction principles of the bioclimatic architecture are important, together with the passive behavior of the building. The high level of insulation of the outdoor partitions [5,6], the exploitation of the structure's thermal inertia [7], the exertion of greenhouses, and the generation of natural air circulations while exploiting particular architectural configurations ensure a significant reduction of the energy required by the building [8]. This requirement should be fulfilled by the proper implementation of renewable energy sources which become primaries energies, banishing traditional energy sources to be secondary energies. However, the implementation of passive interventions must be controlled to avoid an excessive increase of the embodied energy consumed (that is, the amount of energy necessary for the production, transportation to the implementation site, and disposal of the construction materials used by the building industry) that can affect, in a negative way, the energy balance concerning the whole service life of the building [9]. In this type of systems, it becomes very important that the domotics ensure a constant adaptation of the building plant-system [10–12] to both outdoor climatic conditions and indoor thermohygrometric demands [13].

This paper describes a building passive intervention on residential structures [14], characterized by low population density, for the realization of a natural ventilation system. This is why it is essential to point out how proper ventilation is important to maintain healthfulness in spaces, thus avoiding "sick building syndrome" and contributing at the same time to thermohygrometric comfort [15]. The suggested system exploits the principle of solar chimneys [16] in the summer, their ability to ensure the necessary air exchange in those environments, and controlling the energy costs of the building due to the free-cooling process. Unlike the traditional implementation of solar chimneys, the main feature of the suggested configuration is to supply the chimney due to the presence of a plate exchanger placed on the chimney floor, which exploits the natural forces of air floatation, characterized by different densities. The energy source used, deriving from a renewable source, is the heat stored in a solar pond [17]. In this way the suggested configuration observes the Directive EPBD 2.

The fluid-dynamic phenomena ensuring the natural ventilation depend on the results obtained in previous studies [18,19], carried out through the FLUENT calculus code.

## 2. Description of the Suggested Configuration

This study examines a small residential building formed by two floors above ground (Figure 1). There is a solar chimney, with a diameter of 1 m and a height of 11 m, inside the structure to activate the natural ventilation in the building. At the base of the chimney there is a plate exchanger constituting the floor. The heat used to heat the plate, hence the air inside the chimney, is provided by a solar pond placed near the building [20]: in the closed circuit, which exploits the natural convection

forces affected by the density difference between the warmer water produced and the returning colder water, there is an amount of water circulating and functioning as a convective heat transfer fluid between the plate floor in the chimney and an exchanger placed in the deepest layers of the solar pond.
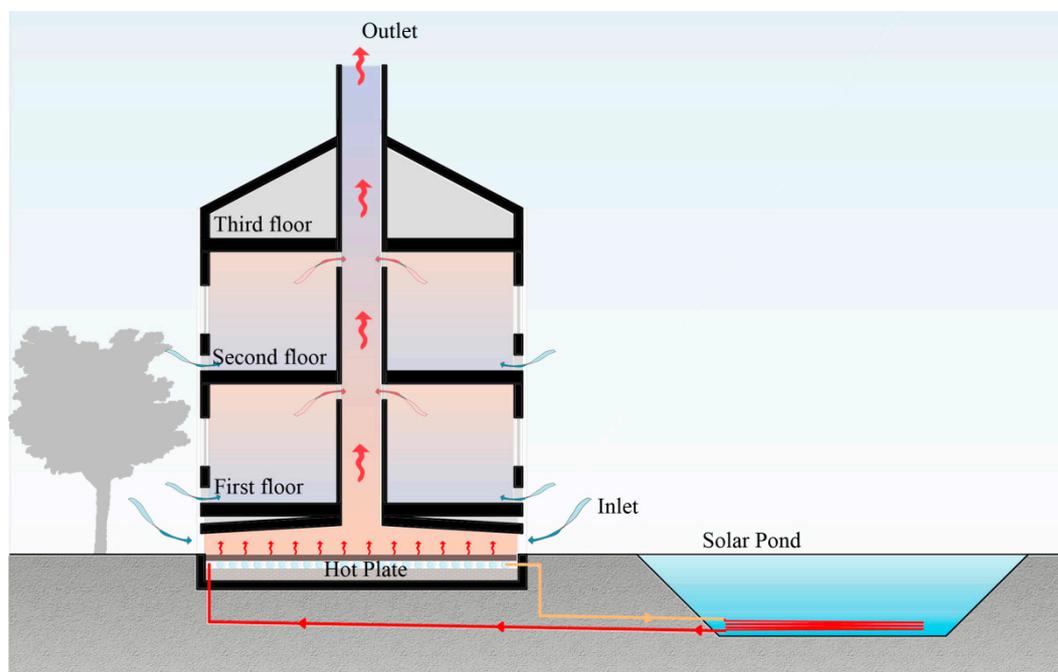


**Figure 1.** Functional diagram of the solar chimney supplied by the solar pond for the natural ventilation of residential buildings.

At the base of the chimney, beside the plate floor, there are outdoor air intake grids. The air coming from outside, due to an increase in temperature of the hot plate, will flow into the chimney and will travel upward [21].

The floors above the chimney present two ventilation grids (for each floor). The environments have a grid in the upper part, entering into chimney, whereas the second grid is placed lower than the other, and takes in air from outside.

The upward movement of the air inside the chimney, due to an inductive effect, withdraws the air from the environments, thus establishing a natural ventilation where the air coming from outside is withdrawn from the grids placed in the lower part of the environment. The natural ventilation effect starts when the outdoor air temperature is sufficiently low; in this way it will not increase the indoor temperature of the spaces [22]. This is determined by the climatic conditions characterizing the site where the building-plant system is located, and occurs at night in those climates where there is a sufficient temperature difference between day and night. Natural ventilation created by the system has the main goal of ensuring the necessary air exchange and, at the same time, contributes to cooling the environment of the building during the day, representing a benefit of improved air quality (due to an air exchange) and the resulting free cooling.

If this occurs properly, it is possible to control the amount of airflow going through through the air vents, according to the temperature of the incoming air from outside [23]. To make the incoming air a benefit for the environments, the air temperature withdrawn from outside cannot have higher values than the optimal temperature that should be maintained in the spaces (26 °C); it must not be too low

though, to avoid the so-called cold drafts (it must not be lower than 8 °C with respect to the inside temperature, hence it must not be lower than 18 °C). Due to these particular vents, it is possible to control the air flow coming from outside only if it presents this temperature range.

Regarding the lower plate supply, there is a heating process through the heat stored in a solar pond placed next to the structure. The heat supplied to the plate at the base of the chimney is activated by a natural circulation hydraulic circuit transferring, through an exchanger placed at the bottom of the pond, the stored heat. In conformity with the nZEB construction philosophy, to implement this circulation without using pumps, and the reduced energy consumption determined by it, an old method of planning heat systems was used. Due to Archimedes' principle, based on the fact that water has different density according to its temperature, a thermohydraulic circuit allowing water to circulate spontaneously [24–26], at low speed, overcame the load losses of the circuit. This is why an exchanger was placed at the bottom of the pond, to obtain enough height difference with respect to the plate at the base of the chimney. This height difference, together with a right measurement of feed and return pipe diameters, respectively, of the warmer water exiting from the exchanger into the pond and the colder water exiting from the chimney plate, allows a natural circulation; thus the heat exchange between the heat source (pond) and the thermal sink (chimney plate).

It is important to remember that solar ponds are pools with a depth range of 80–150 cm, insulated from the soil, and at the bottom are characterized by a material with a high absorption coefficient of solar radiation. They contain a salt water solution. The main goal of solar ponds is to store thermal energy generated by solar radiation; this energy storage occurs in the deepest layers of the pond where, because of a higher density of the salt solution, there is a stratification. The high density of the solution reduces, and almost stops, the natural convection. The result is that heat loss of the pond surface moving outward is minimum. These phenomena determine temperatures of 70–80 °C or even higher [27] in the deepest layers of properly-constructed ponds, according to climatic conditions of the site where the pond is located. If the energy withdrawal of the heat exchanger in the pond maintains the range (between 20 W and 40 W for each m$^2$ of the pond), due to the contribution of the radiant energy, which in the daytime the pond receives from the sun, it is possible to keep the pond at a constant temperature of during the whole season of use. This condition permits a constant temperature at the plate at the base of the chimney, regardless of outdoor climatic conditions [28], thus ensuring the ventilation of the building spaces.

The whole system presents an energy-oriented mechanism: this system works without the participation of traditional energy sources [29,30] (except for the embodied energy employed during the construction of the system).

## 3. The Computational Fluid-Dynamics Model

The bibliography [18,19] shows the equations describing the physical phenomena inside the domain simulating the themal-fluid dynamic behavior of the chimney, which are: continuity equation, the momentum equation, and energy balance (energy conservation equation). In particular, for what concerns the equation on the axis of the chimney, it was assumed the Boussinesq approximation, which considers the density for each term as a constant value, except for the potential energy.

Moreover, for natural convection systems it is necessary to consider the value of the Rayleigh number that can be used to determine whether the flow is laminar or turbulent:

$$Ra = \frac{g\beta(T_H - T_C)L^3}{v\alpha} \tag{1}$$

where $T_H$ and $T_C$ are, respectively, the maximum and minimum temperatures of the system, and $L$ is the characteristic dimension of the flow. If the collector height is taken as a characteristic dimension, the value of the Rayleigh number of the system examined is higher than the critical value $Ra > 10^9$.

For what concerns the stationary and two-dimensional case, those equations describing the system with an incompressible fluid are:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho\overline{u_i' u_j'}\right) - \rho\beta(T - T_0)g_i \tag{3}$$

$$\frac{\partial(\rho u_i T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\lambda}{C_p}\frac{\partial u_i}{\partial x_j} - \rho\overline{u_i' T'}\right) \tag{4}$$

$$\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon + S_k \tag{5}$$

$$\frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right) + C_{1\varepsilon}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{6}$$

where $G_k$ and $G_b$ are respectively the turbulent kinetic energy production caused by the mean velocity gradients and the floating forces.

The following are the surrounding conditions:

- Chimney walls and adiabatic hot plate covering;
- Constant temperature of the hot plate;
- Absence of wind velocity in correspondence of the chimney walls;
- Pressure; temperature and intensity of the turbulence set to a certain distance both at the entrance of the hot plate and the exit of the chimney;
- Conditions of the temperature and pressure in the assigned spaces.

For what concerns the standard turbulence model, the constant values are:

$$C_{1\varepsilon} = 1.44\ C_{2\varepsilon} = 1.92\ C_{3\varepsilon} = tanh\left|\frac{v}{u}\right|\ C_\mu = 0.09\ \sigma_k = 1.0\ \sigma_\varepsilon = 1.3 \tag{7}$$

Using the software FLUENT, the domain of the chimney and the thermal-fluid dynamic phenomena were simulated through a formulation of the control volumes by applying the method to the finite differences. To obtain a sufficient approximation of the turbulent behavior of the fluid near the wall, the "standard near wall function" method was employed. Pressure and velocity equations were solved through the SIMPLEC algorithm, together with a second order discretization scheme.

The computational domain is shown in Figure 2. It contains the area formed by the air collector, the chimney, and the rooms. A wide external region was placed over the chimney outlet in order to fix

appropriate boundary conditions for the pressure outlet. At the walls, "no slip" and "adiabatic" conditions are imposed. The horizontal wall, acting as thermal storage, is characterized by a fixed temperature. Temperature and pressure at all inlets of the domain present the same values of outdoor ambient. No radiative heat transfer is considered.
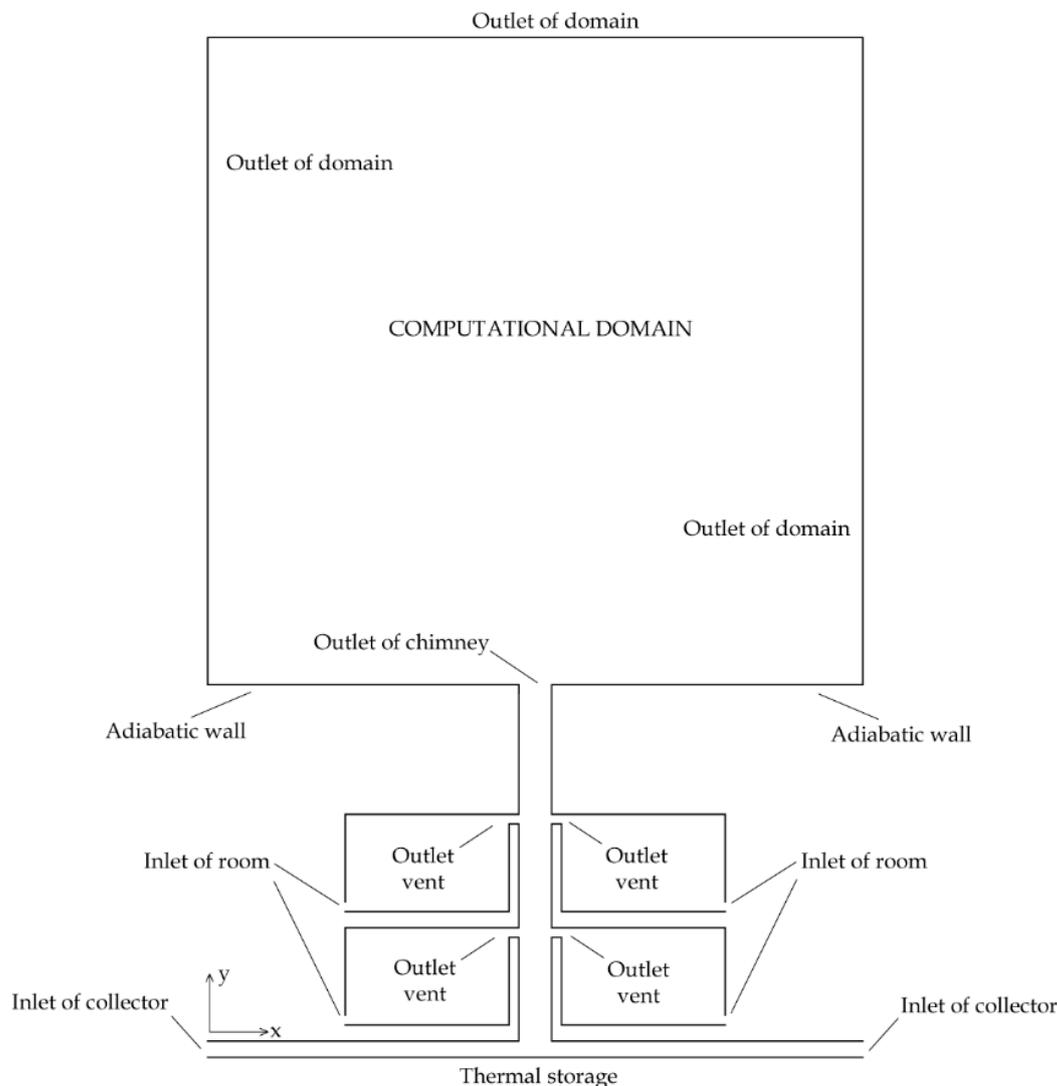


**Figure 2.** Scheme of the computational domain.

In order to validate the code, the case of a chimney with adiabatic walls was calculated for different values of outdoor air temperature and thermal storage temperature. The values of average velocity inside the chimney (at the axis) were compared with analogue experimental results available in the literature [18,19,31], as reported in Figure 3 and Table 1, showing a satisfactory agreement (<10%).

**Table 1.** Chimney velocity: comparison between experimental results and the present study.

| Tp (°C) | Te (°C) | $V_{chimney}$ (m/s) (at the Axis) | | Err (%) |
|---------|---------|---------------------------|----------------------------|---------|
| | | C.B. Maya *et al.* [31] | Present Study [18,19] | |
| 24.00 | 17.80 | 1.64 | 1.50 | −8.26 |
| 21.90 | 17.00 | 1.34 | 1.27 | −5.09 |
| 40.50 | 27.80 | 2.88 | 3.15 | −9.51 |
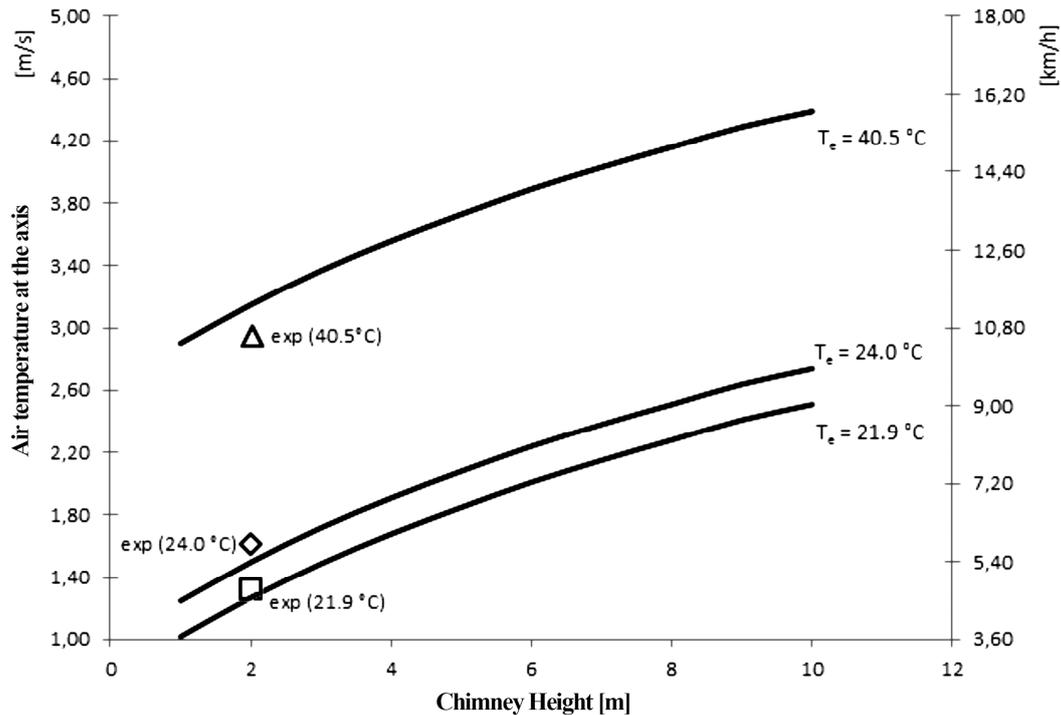
**Figure 3.** Chimney velocity: comparison between experimental results and the present study.

## 4. Results and Discussions

Previous studies [18,19] examined the fluid dynamics of the chimney and the resulting data (concerning the air flows available, according to the functioning conditions of the system based on the climate of the site) are examined.

Figures 4 and 5 show both the total flow and the flow of each vent in every floor of the building, whose value increases when the temperature of the plate gets higher; hence, the plate at the base of the chimney should be warmed, until reaching the maximum temperature value available, through the solar pond.

From the data reported in the bibliography it can be noticed how, in the tropical climates and those temperate zones near the tropics, the temperature of a solar pond can reach values between 70 and 80 °C [20].

It is possible to keep this temperature constant if the power withdrawn per unit surface of the pond respects the range between 20 and 40 W/m$^2$, due to the presence of solar radiation. In order to take into account the losses caused by the irreversibility of the exchangers and the necessary thermal difference between the pond and the exchanger, a constant temperature of the plate of 60 °C was assumed.

Figure 6 shows how, plate temperature being equal, if the outdoor temperature increases the ventilation of the environments, then the total air flow of the chimney will be higher. This behavior is the peculiarity of the configuration suggested. The increased ventilation, when the outside temperature gets higher, determines the free cooling effect every time the enthalpy level of the outdoor air is slightly different from the indoor temperature.
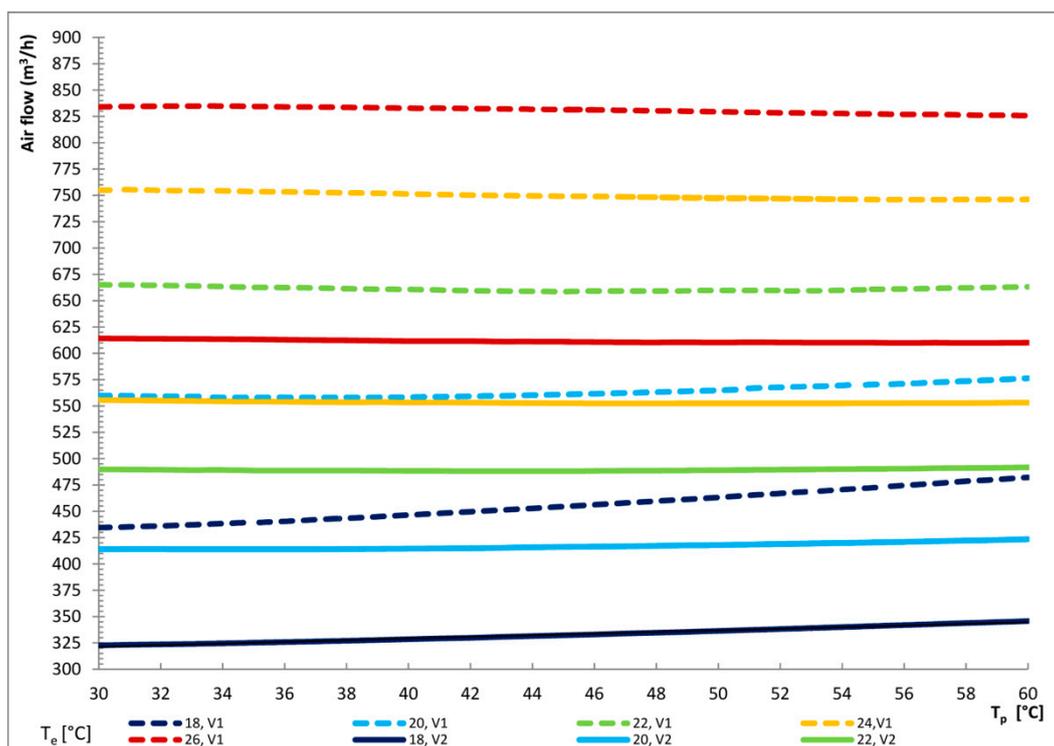
**Figure 4.** Trend of the air flows near the vents in the following floors ($V_1$: vent at first floor; $V_2$: vent at second floor) according to the temperature of the environment ($T_e$) and the temperature of the plate ($T_p$).
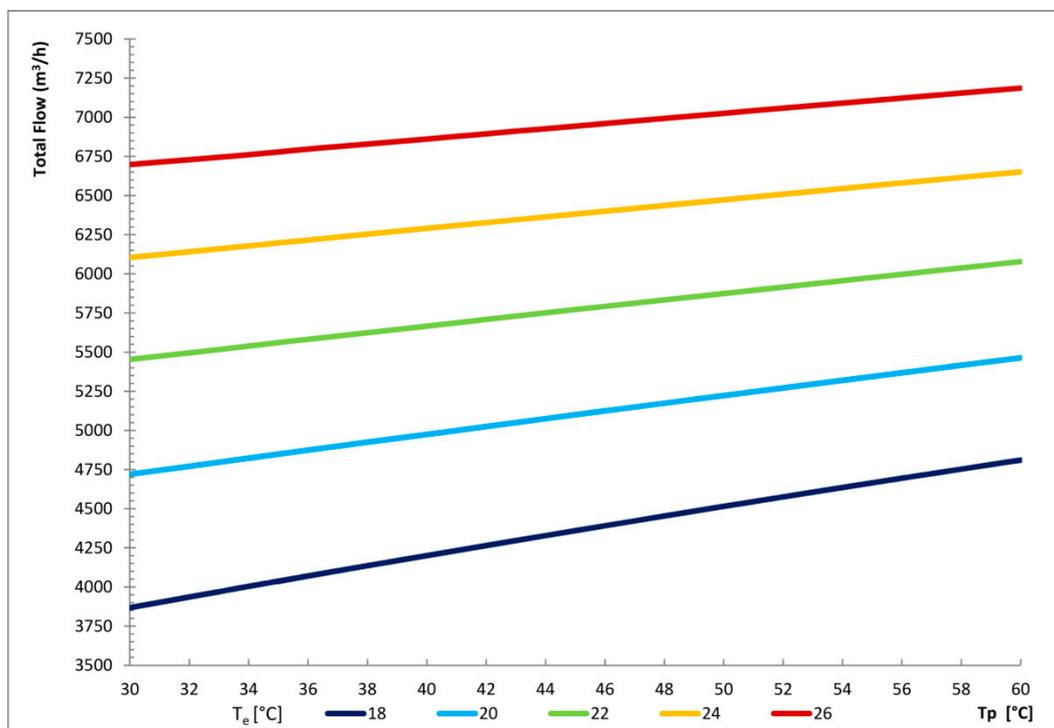


**Figure 5.** Trend of the total air flow near the chimney according to the temperature of the environment ($T_e$) and the temperature of the plate ($T_p$).
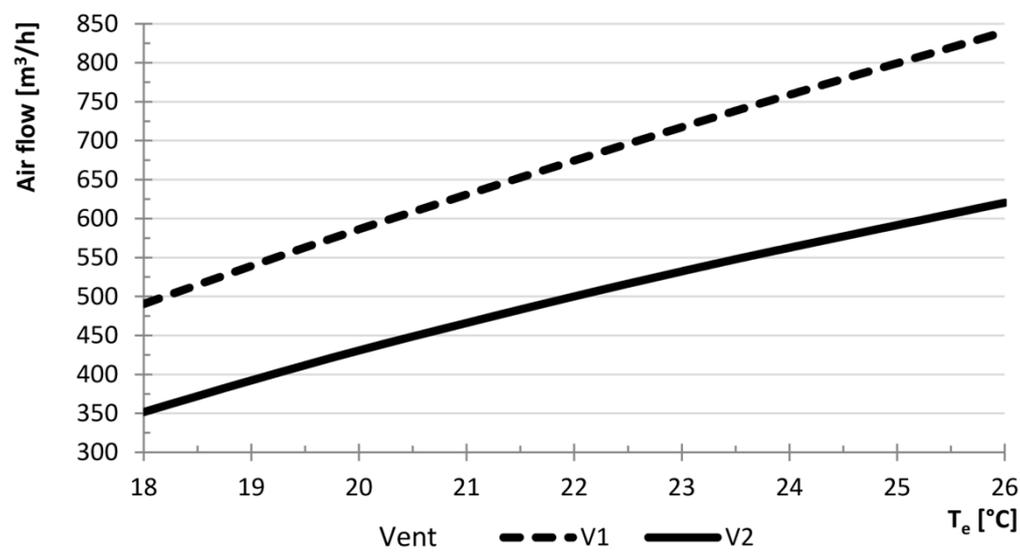
**Figure 6.** Trend of the air flows near the vents in the following floors ($V_1$: first floor; $V_2$: second floor) according to the temperature of the outdoor environment ($T_e$) with a plate temperature of $T_p = 60$ °C.

Figure 6 shows the trend of the air flow in the environments of each vent and how they vary according to the outdoor temperature, while keeping the plate temperature constant ($T_p = 60$ °C). It can be seen how vent 1 (first floor) is characterized by an air flow of 490 m³/h for an outdoor temperature of 18 °C and 840 m³/h for an outdoor temperature of 26 °C. The minimum value of the air flows in the first floor is higher than that present in the second floor. Considering the same outdoor air temperature differences, vent 2 (second floor) ensures a ventilation air flow that can vary from 350 to 620 m³/h. Therefore, even if the air flow presents minimum values in the floor considered less advantageous, if it is assumed for each vent a minimum air exchange of 0.3 vol/h (air exchange in conformity with the standards [32]), every vent can ensure an air exchange for those environments with a volume of about 1100 m³. When the outdoor temperature gets higher, the air flow increases with respect to the one necessary for the ventilation, thus representing a contribution to the free cooling of the environment with some savings regarding the energy consumption of the building and the thermal comfort of occupants of the indoor environment.

Figure 7 represents the trend of the necessary heat for the plate at the base of the chimney to activate the natural ventilation. It is possible to see how, if the outdoor temperature increases, the power required by the plate decreases, due to a lower temperature difference; hence, less energy will be withdrawn from the pond. It is clear that the thermal exploitation of the pond will have to be modulated according to the outdoor climatic conditions.
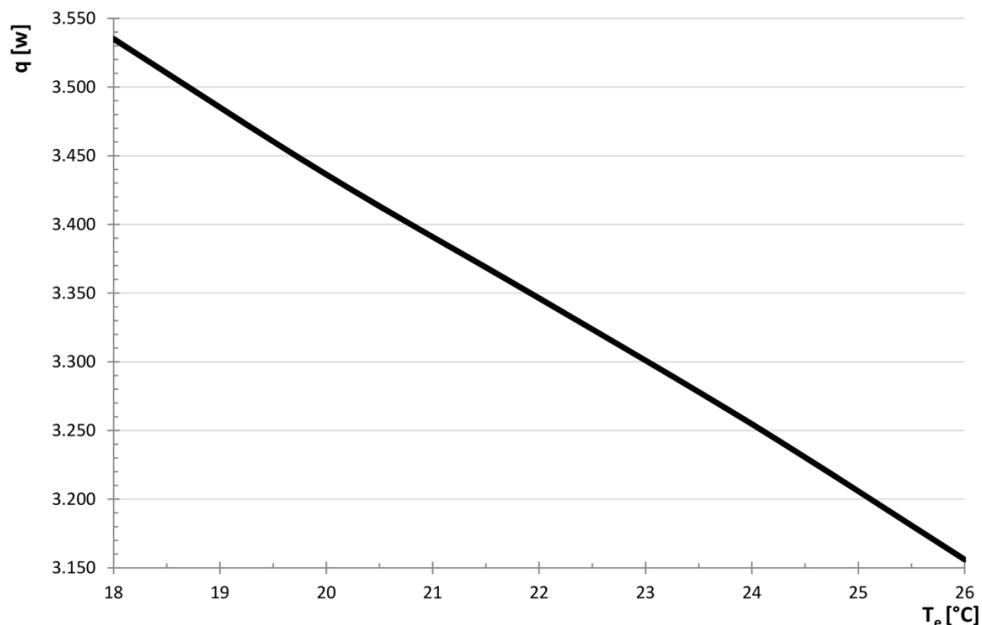
**Figure 7.** Trend of the heat power required by the plate (q) at the base of the chimney according to outdoor air temperature ($T_e$).

While considering the power required by the plate (Figure 7), and assuming that the power withdrawn from the solar pond is of 20 W/m$^2$, 30 W/m$^2$, and 40 W/m$^2$ [20], the surface of the pond (Figure 8) necessary to provide the heat required ranges from 80 m$^2$ to 180 m$^2$.
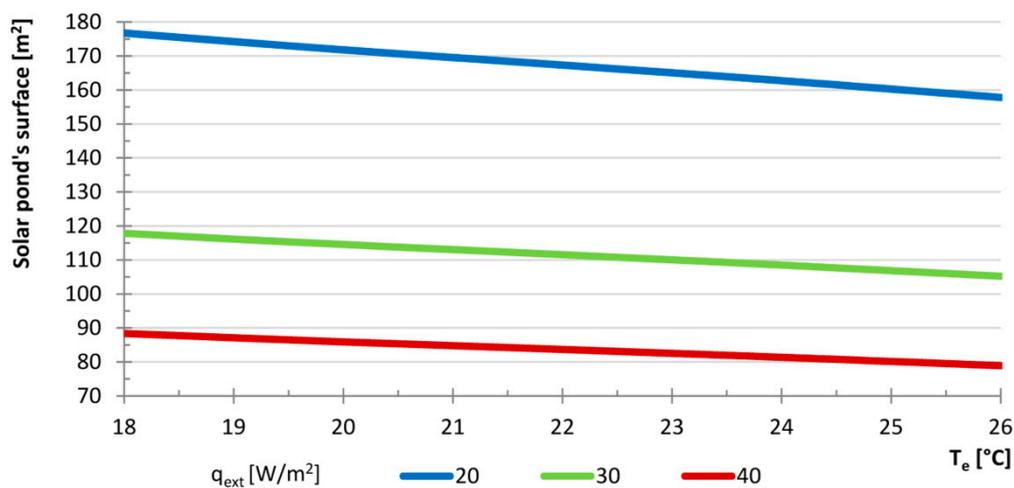


**Figure 8.** Necessary surface of the solar pond according to the minimum outdoor reference temperature ($T_e$) and the heat collected per unit surface of the pond ($q_{ext}$).

However, since the purpose is to use zero energy systems, it is expected that the plate power circuit be a natural circulation system [24–26]. In order to activate this circulation, a height difference must be ensured between the heat source (the solar pond) and the plate at the base of the chimney.

By examining Figure 9, the diameter dimensions of feed (exchanger at the bottom of the pond) and return (plate at the base of the chimney) water pipes can be measured, with the input being H/L; that is, the ratio between the height difference and the length of the circuit connecting the exchanger at the bottom of the pond and the plate at the base of the chimney.
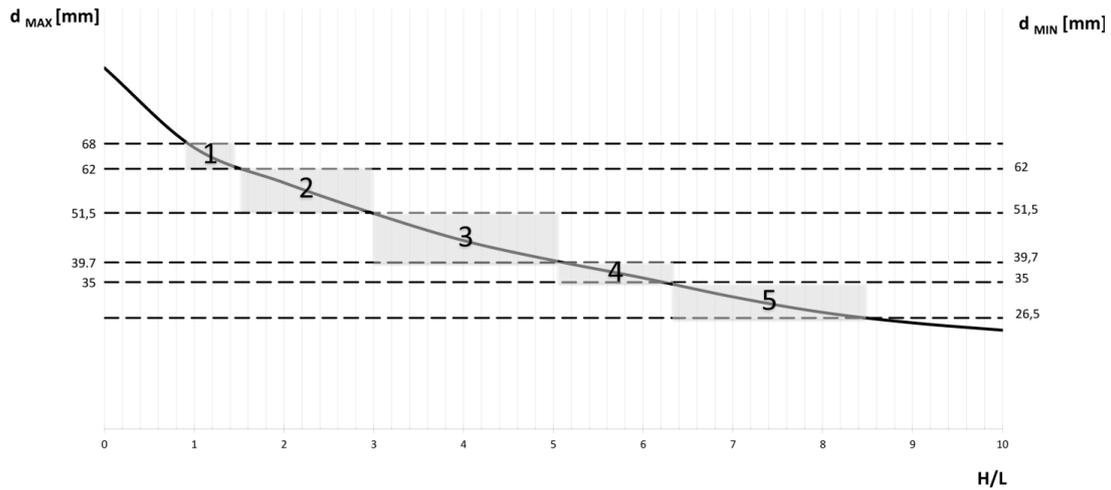
**Figure 9.** The zones painted and numbered furnish information about the feed and return diameter according to the ratio H/L: (1) feed diameter: 68 mm + return diameter: 62 mm; (2) feed diameter: 62 mm + return diameter: 51.5 mm; (3) feed diameter: 51.5 mm + return diameter: 39.7 mm; (4) feed diameter: 39.7 mm + return diameter: 35 mm; (5) feed diameter: 35 mm + return diameter: 26.5 mm.

The natural ventilation system suggested can represent a benefit in terms of free cooling of the building when the outside temperature values range between 18 and 26 °C. Figure 10 reports some areas where it is possible to exploit this type of system for the natural ventilation; it must be considered, besides adequate outdoor air temperatures, he solar radiation values must be able to maintain the correct temperature of the solar ponds [33]. The following image reports those months characterized by these climatic conditions.
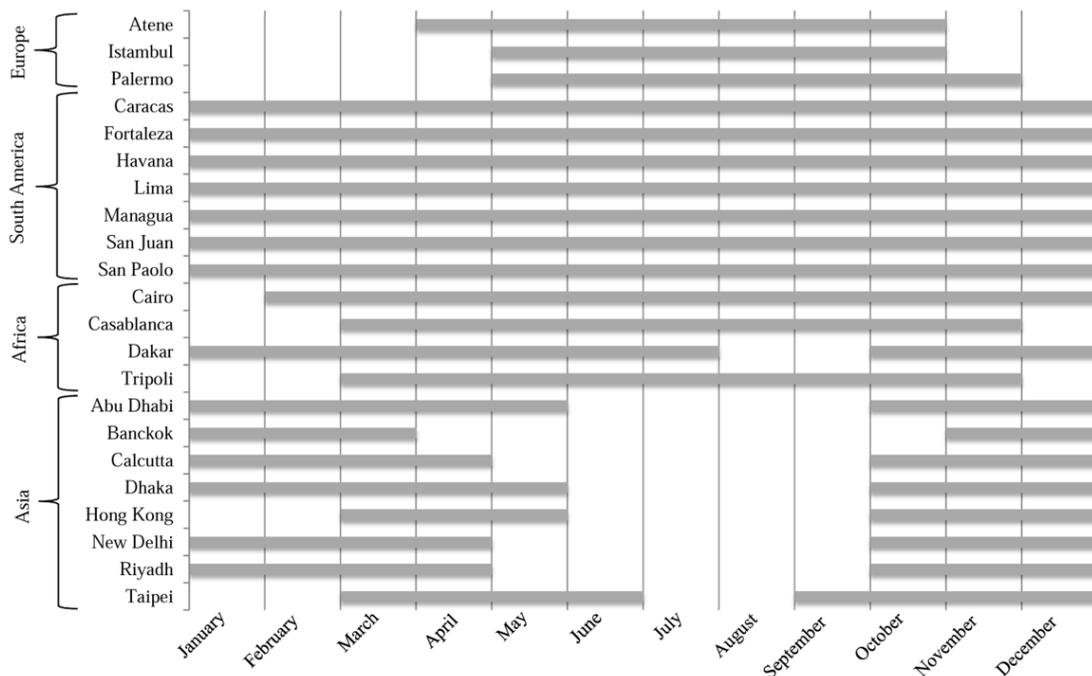


**Figure 10.** Areas where it is possible the exertion of the system suggested and months of operation.

## 5. Conclusions

This case study showed the possibility of obtaining the necessary air exchange in those environments in buildings with low inhabitant density, constructed in hot climates characterized by both a thermal inversion between days and nights and adequate solar radiation (in a way it can support the correct function of solar ponds and use them as an energy source). This ventilation was obtained through passive methods without any use of conventional energy. In this way, in addition to guaranteeing the healthfulness of the environments, it is also possible to determine a free cooling process which leads to some savings regarding the building energy requirements. This paper is a contribution to the construction techniques of a nZEB (Nearly Zero Energy Building) [34,35].

These results can be obtained due to the implementation of solar chimneys supplied by a heat source placed at their base [36]. Such configurations allow, due to induction phenomena, the activation of a ventilation process where fresh and healthy air from outside flows into inhabited environments. The air exchange coming from outside flows inside the building to cool the environments and its temperature must have a range of 18 to 26 °C. This necessity confines the natural circulation to a time interval during the day (during the afternoon or night or at the beginning of the day). If the area where this ventilation system occurs presents a hot climate for most of the year, the system can function for a certain time interval saving a significant amount of energy.

To make the system exploit just the energy produced from a solar source useful for the heating of the solar pond, the water functions as a heat transfer fluid circulating between the heat exchanger placed in the deepest (and hottest) layers of the solar pond and the plate placed at the base of the solar chimney. Due to the density differences, this circulation occurs without the use of a pump. The water density in the feed pipe, at a higher temperature, is lower than the density in the return pipe, with a lower temperature. Such difference in density and height, between the exchanger placed in the pond and the plate of the chimney, activate natural convection forces allowing the water to overcome losses in the circuit where it flows and, while circulating, it can transfer the heat of the pond to the solar chimney.

The reader, according to outdoor temperatures of the area where the system suggested must be located, while referring to the graphs reported in this article, can determine: the natural ventilation air flows of a residential building with a low inhabitant density, the dimensions of the area of the solar pond providing heat to this passive system, and the pipes' measurement of a natural circulation system with the goal of transferring heat from the solar pond to the heating plate placed at the base of the chimney.

The results furnished by the simulations assume a windless condition at the top of the chimney. This hypothesis is precautionary. As a matter of fact, the chimney is able to exploit the inductive effect of the wind, which can determine a further increase of the total air flow of the solar chimney, together with some advantages concerning the functioning of the system. While keeping in mind these facts, it is possible to carry out further studies that consider such a configuration.

Exploiting the ventilation generated by the solar chimney in the winter is finally of particular interest, while using the heat stored in the solar pond during the summer to heat indoor environments. This requires a remodulation of the whole system configuration; hence, the necessity to explore new fluid dynamic simulations.

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## Author Contributions

The study was designed by Ferdinando Salata and Massimo Coppi. Anna Tarsitano and Chiara Alippi retrieved the data from yearbooks and professional websites and reviewed the literature related to the research. The results were then analysed by Ferdinando Salata and Iacopo Golasi. Model design and English corrections were undertaken by Iacopo Golasi. Finally, Massimo Coppi, the associate professor of the research group, supervised the work related to the paper and the execution of its various phases. All authors have read and approved the final manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

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