Thermal Performances of a Solar Chimney with Thermal Storage in a Residential Building

Arcuri N., Farfalla G., Bruno R.

Mechanical Engineering Department- University of Calabria – ITALY- V. P. Bucci 44/C – 87036 –Rende (CS)

e-mail: natale.arcuri@unical.it

Abstract

Among the solutions adopted in order to reduce the use of fossil fuels in the cooling of buildings, turning to natural ventilation with outdoor air takes on great importance, when it is found to be of a temperature that is lower than the indoor temperature.
A solar chimney placed at the summit of a pitched roof, formed by a black coloured opaque wall with southern exposure and by three glazed surfaces, capable of accumulating incident solar energy increasing the temperature of the wall, permits the activation of natural ventilation by means of the aspiration of moderate temperature outdoor air, which will cool the building, in particular at night, with a limited, yet continuous air flow rate. The building taken into consideration is situated in the Mediterranean area, where the energy requirement for cooling is comparable with that required for winter heating. An opportune control strategy will either activate the chimney, or not, according to the necessity of the environment to be controlled. Performances of the building equipped with a solar chimney were determined by means of the Energyplus simulation code, varying some parameters such as the section, the height and the storage capacity of the chimney wall. Once the best configuration was identified, seasonal energy evaluations were carried out in both the presence and absence of a conditioning plant in order to evaluate the benefits deriving from the presence of the solar chimney.

1. Introduction

Natural ventilation systems have been widely studied over the last twenty years. One of the principal applications in buildings regards the containment of the indoor air temperature during summer, or the reduction of the required cooling energy, above all in areas like the Mediterranean, with hot and humid climates.

Natural ventilation uses natural forces, such as wind thrust and floating, to introduce fresh air into environments with the aim of eliminating odours, diluting pollutants and increasing thermal comfort. In literature, different systems of natural ventilation are present, including solar wind towers, Trombe walls, double walls and solar chimneys. Solar wind towers are suitable in areas in which buildings are low and wind velocity is sufficient to trigger ventilation. The principal application of Trombe walls is in passive heating. Solar chimneys are passive systems which can be integrated into the construction, or built to the rear and present one or more glazed walls through which solar irradiation strikes the surface of the absorber, increasing the temperature. In this way, the air temperature of the chimney rises and triggers an airflow. Natural ventilation with the use of solar chimneys, does not constitute a novelty, it has been possible to find studies of such systems since the beginning of the twentieth century, yet until the start of the 1970's weight was not given to such systems, favouring conventional cooling systems. The 1970's petroleum crisis pushed research towards passive systems to reduce energy consumption. The studies regarding this are numerous, and one of the most complete analyses was conducted by Bouchair [1,2] who analysed the thermal performance of a 2 meter high and 3 meter wide solar chimney, with a variable depth between 0.1 and 1 meter, and an entry section height of either 0.1 or 0.4 meters. Bouchair obtained the best results in terms of airflow for a height/depth relation of the chimney equal to 10, noting an inverse flow in the case of a thickness greater than 50 centimetres. Hinurlab *et al* [3] conducted a theoretical and experimental study on solar chimneys with a metallic solar wall finding the optimum with a wall which was 2 meters high, 1 meter wide and with a depth of 0.145 meters. Spencer [4] evaluated the inlet conditions and chimney height on performance, encountering an inverse flow in the case of a depth greater than a certain value. These results were used by Spencer to validate two theoretical models. Ong and Chow [5] built a chimney with a height equal to 2 meters, 0.48 meters in width and 1.02 meters in depth. The results obtained have shown a dependence of the mass flow in the chimney on solar irradiation [6]. Chen *et al* [7, 8, 9] investigated the performance of a chimney with the following dimensions: height 1.5 meters, width 0.62 and with a variable thickness of between 0.1 to 0.6 meters, varying inclination and solar irradiation. In this case, it was not possible to find an optimal solution. Other authors have studied the effects of solar chimneys in the presence of a conventional cooling system [10], estimating a load reduction of 30%. Other solutions, to improve the performance of solar chimneys, even in combination with systems which cool the inlet air flow rate, are being studied. Such systems can be evaporative cooling systems [11, 12] or geothermal exchangers [13].

Notwithstanding the numerous studies carried out, it has not yet been possible to establish, with certainty, the performances of such systems, as their functioning is strongly dependent on different parameters, which can be both geometrical or environmental.

The aforementioned theoretical studies were carried out in stationary conditions which do not, therefore, take into account climatic variability and the thermal inertia of the chimney-building system.

2. Case study

In this work, the performances, in dynamic functioning conditions, of a solar chimney placed on a building situated in Cosenza (Italia, latitude 39.31° N) were studied. Such a choice arose from the evidence that the variability of external climatic conditions strongly conditions solar chimney functioning, even with thermal inertia of the building and chimney also intervening in this case. A preliminary analysis was carried out with reference to some consecutive days of characteristic months, in order to determine the performance of the chimney in relation to some geometrical, thermo-physic and environmental parameters. Once the best configuration of the chimney being studied was determined, a performance analysis in dynamic functioning conditions for the entire unheated period was carried out. The building is formed by just one floor, and is divided into several indoor environments, communicating with an entrance above which the solar chimney is placed, see figure 1.

The parameters of the chimney taken into consideration are: the height, the thermal capacity of the chimney walls, and the section of the chimney. The chimney is divided internally by a wall and is glazed on three sides (East, West and South) as shown in figure 2.

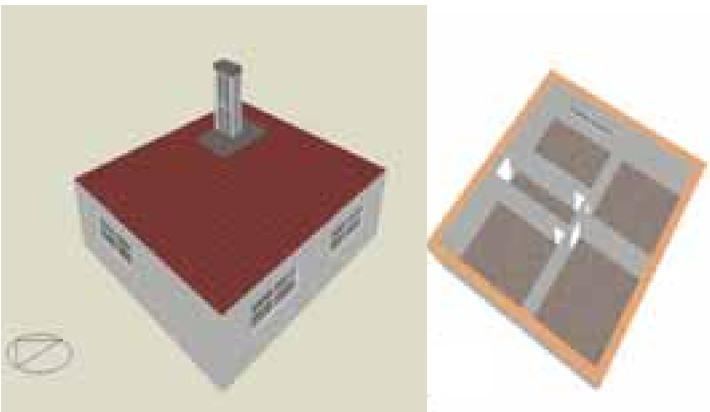

Fig. 1. Reference building equipped with solar chimney

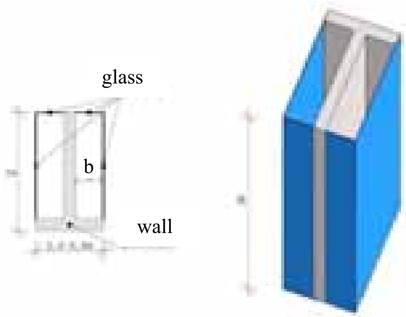

Fig. 2. Representation of the considered solar chimney

In order to evaluate the benefits gained by the environment from insertion of the chimney, the principal variable considered is the hourly temperature of the air in the environments. Furthermore, the number of hourly exchanges of the environment were calculated with the aim of highlighting the flow during the hours in which it is active. The simulations, conducted with Design Builder software which uses Energyplus [14] as a calculation motor, allowed for the evaluating of the system in dynamic conditions, or rather with varying outdoor environmental conditions amongst which are solar irradiation, environment temperature, wind direction and intensity. The preliminary simulations were conducted for four consecutive days each month, paying attention to those carried out during the summer week in which there were maximum temperature and solar irradiation values. The control strategy adopted for each of the four environments provides for the opening of windows and of the eventual chimney when the indoor environment temperature exceeds the set point value, which is equal to 22 °C and contemporaneously the outdoor air temperature is lower than the indoor one. The chimney geometry for the reference case presents a height equal to 2.5 meters, and two sections with width and depth of respectively 80 and 15 cm each (figure 2).

The geometrical parameters that were investigated were the height and section of the chimney. The other parameter analysed was the thermal capacity of the chimney walls. In Table 1 the information on the materials relative to the three types of chimneys considered, starting from external to internal side, are reported.

Table 1 – Properties of the materials of the three chimneys considered

		mm	ρ [kg/m^3]	c_p [J/kg K]	k [W/m K]
CHIMNEY MEDIUM	Black	1	1000	1000	0.3
	Concrete Block Medium	100	1400	1000	0.51
	Black	1	1000	1000	0.3
CHIMNEY LIGHTWEIGHT	Black	1	1000	1000	0.3
	Concrete Block Lightweight	100	600	1000	0.19
	Black	1	1000	1000	0.3
CHIMNEY HEAVYWEIGHT	Black	1	1000	1000	0.3
	Heavyweight	100	2300	1000	1.63
	Black	1	1000	1000	0.3

3. Simulation results

The analyses were carried out in the absence of a conditioning plant, varying one parameter at a time, and comparing the results obtained with the case of natural ventilation without a chimney, with the aim of evaluating the benefits due to the presence of a chimney, compared to ventilation carried out with present apertures. The preliminary study, carried out over four consecutive days in the considered months, highlighted the same behaviour for all the months in which cooling results as being necessary; for simplicity, some trends relative to the month of July are reported.

3.1. Chimney height variations

In figure 3 the indoor air temperature trends and the number of hourly exchanges on the hottest days (24th-27th July) are reported, taking into consideration three chimney heights: 1.5, 2.5 and 3.5 meters. The comparison of the case of natural ventilation without a chimney, also reported in figure 3, highlights the benefit in terms of a reduction of the indoor air temperature. The greatest air exchanges in the presence of a chimney, reported in figure 3, result as being slightly higher for the highest chimney. The analysis highlights, for the case examined, the negligible influence of chimney height on the indoor air temperature.

3.2. Section variations

The simulations carried out highlighted that the dimension of the section assumes an important role on the motion that is generated in the chimney.

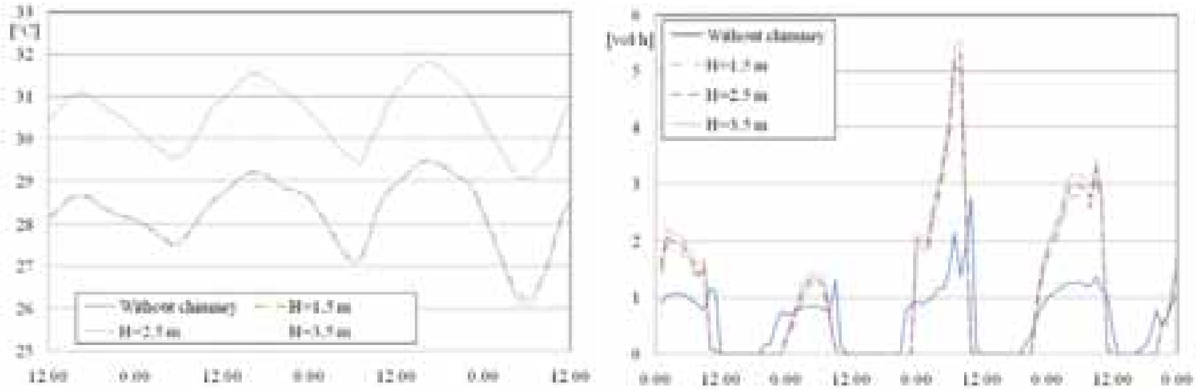

Fig. 3. Trends for temperature and number of air exchanges for the period of 24th – 27th July with varying chimney heights. Absence of conditioning.

In figure 4, the trend for the indoor air temperature is reported and the number of air exchanges obtained for the considered days (24th –27th July) for three "b" dimension values (see figure 2) of the internal section of the chimney: 15, 25 and 35 cm. The comparison of the case in the absence of a chimney, highlights the lower temperature which determines the presence of the chimney system for all the considered sections, even if the greater benefit is to be had with the minor section (b=15 cm). It is interesting to observe that the number of air exchanges grows with the growth of the section, and that therefore greater air exchange does not always mean a lower indoor air temperature. By analysing the cases examined, it was found that with sections greater than the minimum considered, in some hours of the day there is a flow inversion, with a current of air from the top downwards which provokes inflow in environments of an air temperature greater than that outdoors, due to the heating of the air which strikes the hot surface of the chimney, a phenomenon already highlighted by some authors[4].

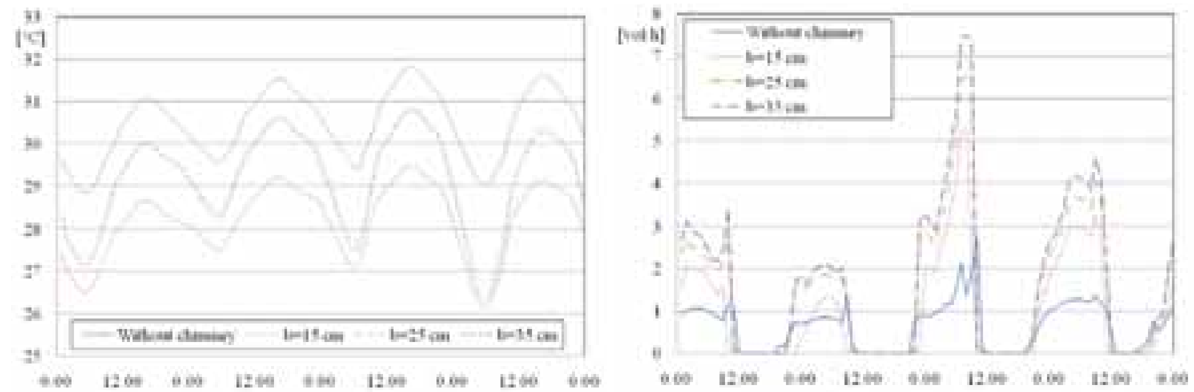

Fig. 4. Trends for the temperature and number of air exchanges for the period of 24th – 27th July with varying chimney sections. Absence of conditioning.

3.3. Thermal capacity variations

In dynamic functioning conditions, the thermal capacity of the wall plays an important role since, in the presence of solar irradiation it heats, accumulating energy internally which is then yielded to the air when an airflow is present internally. In order to evaluate its influence three wall types were taken into consideration: light, average and heavy, with reference to their thermal capacity, whose properties are reported in Table 1.

In figure 5, internal air temperature trends are reported, which were obtained with the three wall typologies, and compared with the reference ones in the condition of the absence of a chimney. The results obtained highlight that the best results are obtained with average or heavy walls, to highlight that it is advisable to use a wall which has a thermal capacity which is not very low, in order to exploit the thermal storage capacity of the chimney.

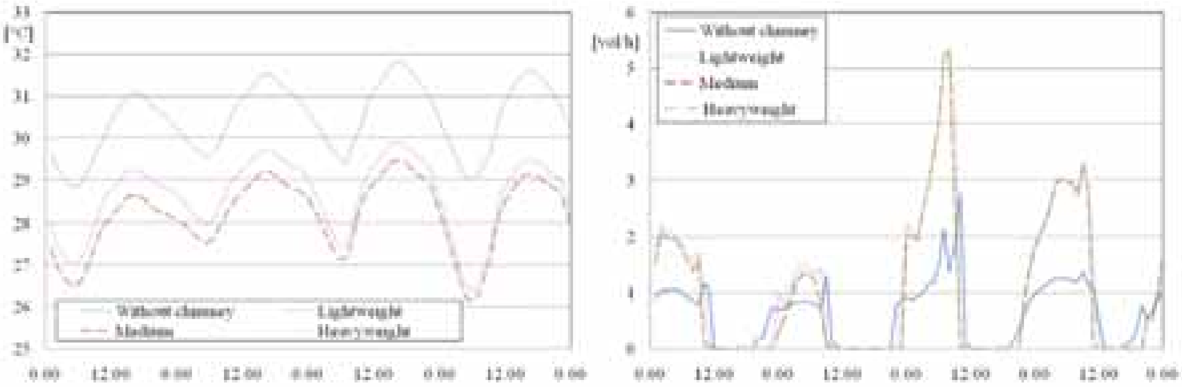

Fig. 5. Trends for the temperature and number of air exchanges for the period of 24th – 27th July with varying chimney thermal capacities. Absence of conditioning.

4. Energy analysis

In order to evaluate the seasonal energy performance of the considered building, in the presence and absence of a solar chimney, a simulation was carried out for the entire unheated period, employing the previously used control function.

With such an aim, the best configuration identified in the previous simulations was used: height equal to 2,5 meters in order to be able to benefit, compared to the case of 1,5 meters, of the greater number of exchanges; sections equal to 15 cm: such a solution would allow for the obtainment of the lowest air temperature; thermal capacity of the average chimney walls, presenting the same effects as the heavy one.

With this configuration simulations of the building were carried out for the period from the 1st of April – 31st of October, in two different functioning conditions: absence and presence of a conditioning plant which does not permit the indoor air temperature to exceed 26°C.

4.1. Evaluation in the absence of a conditioning plant

In the absence of a conditioning plant, the benefit deriving from the presence of the solar chimney is translated into a lower indoor air temperature compared to when there is no chimney.

In order to carry out a monthly and seasonal evaluation it was necessary to determine, for each month, and for the entire period, the number of hours in which the indoor air temperature was found to fall within the interval (t-0,5) – (t+0,5). The percentage frequencies, in terms of fractions of hours where the indoor air temperature was found in each interval were found, and successively the cumulative frequencies were determined.

In figure 6 percentage frequencies of the indoor air temperature in the presence and absence of a chimney are reported. It is possible to observe that the presence of a chimney avoids temperatures of 31°C and greatly reduces the number of hours with a temperature in the interval comprising between 27 and 30°C. The benefit of reducing the percentage of hours in which indoor air has higher temperatures, was encountered in all the months from May to September inclusive. The difference between the two cumulated frequency curves of the indoor air temperature with and without a solar chimney reported in figure 7, permits the highlighting of the lowering of the indoor air temperature in terms of percentages: in particular, the hours in which the air temperature is greater than or equal to 28°C diminishes from 62% to 30%.

Fig. 6. Frequency of the indoor air temperature with and without a chimney. August.

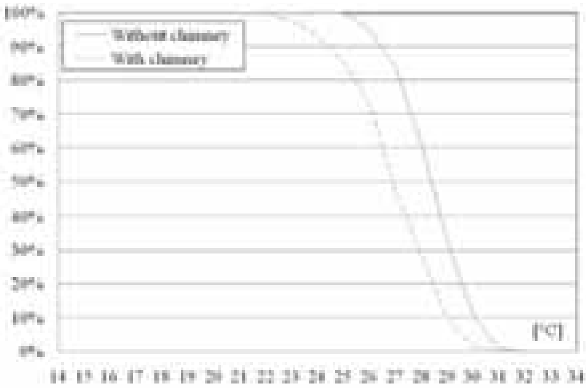

Fig. 7. Cumulated frequency of the indoor air temperature with and without a chimney. August.

A similar statement can be made for the period comprising the months of June and September when it is necessary to refrigerate. In figure 8, the difference between the two cumulated frequencies allows for the highlighting of the benefits deriving from the presence of the chimney in the considered period.

As an example, the percentage frequency with which the indoor air temperature is found to be of a temperature greater than, or equal to 26°C diminishes by about twenty percentage points (from 64% to 40%).

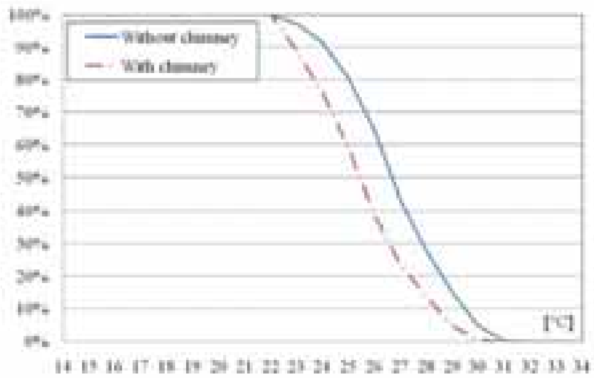

Fig. 8. Cumulated frequency of the indoor air temperature with and without a chimney referring to the period from June-September.

4.2. Evaluation in the presence of a conditioning plant

Often, a solar chimney is associated with the presence of a conditioning plant which does not allow the indoor air temperature to rise above 26°C. The benefits derive from the activation of the chimney in the presence of an outdoor air temperature of less than 26°C, in such a case natural ventilation contributes to the cooling of the environments. Another advantage is linked to the nocturnal cooling of the building structure, it permits the plant to start later, and when it activates the building structure is less hot.

The quantification of the benefits obtained can be carried out by evaluating the diminishment of the cooling requirement of the building in the presence and absence of a chimney.

In figure 9 and table 2 the refrigerant energy requirements of the conditioning plant in the presence and absence of a solar chimney are reported.

In the months of April, May and October, there is no requirement as the indoor temperature does not meet the set point value of (26°C). The greatest benefits are encountered during hot months: in July and August the saving is around 60%, while for intermediate and greater months, a reduction in the seasonal requirement of 66% is obtained.

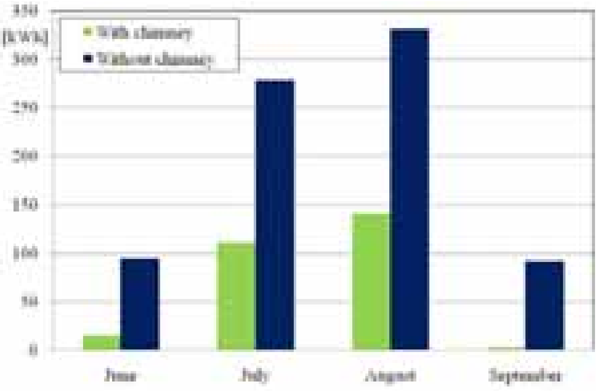

Fig. 9. Energy requirement for summer cooling, with and without a solar chimney.

Table 2. Energy requirement for summer cooling, with and without a solar chimney.

Month	Cooling Energy provided [kWh]		
	Ventilation without chimney	Ventilation with chimney	Energy saving
June	94	15	84%
July	278	111	60%
August	331	141	58%
September	92	2	97%
Season	**795**	**269**	**66%**

5. Conclusions

The analysis carried out in dynamic functioning conditions initially permitted the evaluation of the influence of the three parameters taken into consideration: height, section and thermal capacity of a solar chimney placed on buildings situated in areas with a Mediterranean climate.

It was observed how the height and section of the solar chimney are parameters which are mutually influenced, and the choice of one necessarily depends on the evaluation of the other. The thermal capacity of the walls is, instead, a parameter which is mainly recorded during summer when solar irradiation and outdoor temperatures are higher. The presence of a solar chimney strongly influences natural ventilation. The simulations carried out for the entire unheated period showed that, in the absence of a conditioning plant, it allows for more moderate indoor air temperatures, especially during hot months. In the case of the presence of a conditioning plant, the benefits deriving from the presence of a chimney are notable, having obtained a reduction of 66% of the thermal energy required to maintain the building at a temperature that does not exceed 26 °C.

References

[1] Bouchair A., *Solar induced ventilation in the Algerian and similar climates*, PhD thesis, *Department of Civil Engineering*, The University of Leeds, 1989.
[2] Bouchair A., *Solar chimney for promoting cooling ventilation in southern Algeria*, Buildings Services Engineering Research and Technology 1994, 15:81–93.
[3] Hirunlabh J, Kongduang W, Namprakai P, Khedari J. *Study of natural ventilation of houses by a metallic solar wall under tropical climate, Renewable Energy* 1999, 18:109–19.
[4] Spencer S. *An experimental investigation of a solar chimney natural ventilation system*, Master thesis, *Department of Building*, Civil and Environmental Engineering, Concordia University; 2001
[5] Ong K, Chow C. *Performance of a solar chimney, Solar Energy* 2003;74:1–17.
[6] Ong K. *A mathematical model of a solar chimney, Renewable Energy* 2003; 28:1047–60.
[7] Chen Z, Bandopadhayay P, Halldorsson J, Byrjalsen C, Heiselberb P, Li Y. *An experimental investigation of a solar chimney model with uniform wall heat flux, Building and Environment* 2003; 38:893–906.
[8] Ramadan Bassiouny, Nader S.A. Korah *Effect of solar chimney inclination angle on space flow pattern and ventilation rate, Energy and Buildings* 41 (2009) 190–196
[9] E.P. Sakonidou a,b, T.D. Karapantsios, A.I. Balouktsis, D. Chassapis *Modeling of the optimum tilt of a solar chimney for maximum air flow, Solar Energy* 82 (2008) 80–94
[10] Khedari J, Rachapradit N, Hirunlabh J. *Field study of performance of solar chimney with air-conditioned building, Energy* 2003; 28:1099–114.
[11] Chakraborty J, Fonseca E. *Analysis and evaluation of a passive evaporative cool tower in conjunction with a solar chimney* Plea2005 – the 22nd conference
[12] M. Maerefat, A.P. Haghighi *Natural cooling of stand-alone houses using solar chimney and evaporative cooling cavity, Renewable Energy* 35 (2010) 2040–2052
[13] M. Maerefat, A.P. Haghighi *Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney, Renewable Energy* 35 (2010) 2316-2324
[14] *EnergyPlus* U.S. Department of Energy