MODELING A SOLAR CHIMNEY FOR MAXIMUM SOLAR IRRADIATION AND MAXIMUM AIRFLOW, FOR LOW LATITUDE LOCATIONS

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ABSTRACT

Numerous researches have shown the possibility to enhance indoor natural ventilation in buildings by using inclined solar chimneys, although most of them usually include determining an optimum tilt for the absorber, considering an inclination angle between maximum solar irradiation and best stack height. This paper resumes the investigation of a possibility to optimize solar irradiation on the absorber plane and also guarantee a considerable stack height, by using a chimney extension, which would be responsible to maintain a minimum height for the system, independently from the absorber inclination. Results of a building simulation were compared with outputs from an experimental test cell for calibration. Theoretical analyses were developed, aiming to evaluate the proposed system's performance. Results testify a significant airflow enhancement, demonstrating its viability to use as a natural ventilation strategy in a Brazilian low latitude location.

INTRODUCTION

Natural ventilation in buildings is an important strategy to remove indoor air pollution and dilute contamination. For Brazilian tropical climate, it is also a recommended strategy to provide thermal comfort through passive cooling in most of the territory (ABNT, 2005).

The strategy is suitable to use when indoor air temperature is higher than outdoor, which could occur due to high internal loads and/ or gains through solar radiation. When this situation occurs, natural ventilation is a strategy that helps obtaining thermal comfort, by evaporation of skin's sweat and consequent cooling effect. An airflow of 0.5m/s, for example, causes a cooling effect of 1.2°C on an indoor occupant (Freixanet and Viqueira, 2004).

A way of naturally induce air movement inside buildings is by using the solar chimney principle. It consists of using energy available from solar radiation to heat up the air and induce stack effect, through the enhancement of pressure and temperature differences between inlet and outlet openings. It is an alternative system to provide natural ventilation inside a building, in locations where winds are not frequent, as it can occur in densely urban areas, for example.

The solar chimney is composed by a solar collector with two parallel plates – a glass cover and an absorber plate – that heats up the air, enhancing the greenhouse effect and inducing it to move upwards. Consequently, air from the internal space moves towards the chimney inlet and outdoor air enters the space through the inlet openings of the room (Figure 1).

The efficiency of solar chimneys depends, among other factors, on the intensity of solar radiation that reaches the glass cover. Since the angle of incidence of solar radiation on a surface varies with latitude and time of the year, it becomes advantageous using inclined solar chimneys at locations near the Equator, due to the reduction of the incidence angle and consequent increase of irradiance on the glass cover.

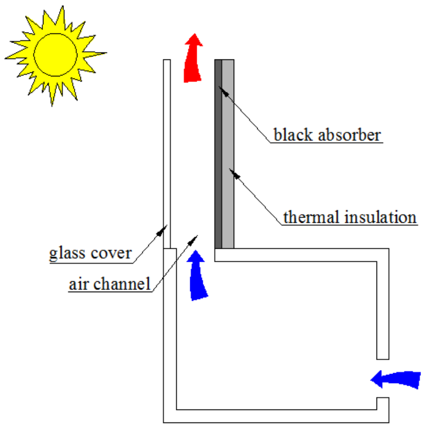


Figure 1 Schematic section of a solar chimney

One of the first works to take into consideration the possibility of varying the chimney's tilt is from Bansal et al (1993), performed in Jaipur, India (26°53' latitude north). They developed a theoretical study through a steady state mathematical model. The study included different chimney sizes and different discharge coefficients. The best results indicated an induced airflow of 331m³/h for a solar collector area of 2.25m², 0.15m depth of air channel, 30° of inclination of the collector with horizontal and 1000W/m² of solar irradiation.

Also in India, Mathur et al (2006) used experimental and theoretical methods to investigate the effects of the solar chimney's inclination angle in the ventilation rates, during summer months. The mathematical modeling consisted of developing three steady state equations of energy balance for glass, air and black plate. The experiment aimed to validate the theoretical solution. A cubical wooden chamber of 1m edge was built, with a 45° tilt solar chimney with 1m^2 of solar collector area and 0.35m^2 of air gap.

Experimental and theoretical studies had a good agreement. Results have shown that solar chimney's optimum tilt varies from 45° to 60°, depending upon the latitude. The theoretical model indicated an average air velocity of 0.18m/s inside the chimney for a solar irradiation of 750W/m^2 and ambient temperature of 40°C. For the same conditions, the experiment indicated a velocity of 0.22m/s.

Bassiouny and Korah (2009) studied the effects of solar chimney's inclination angle on ventilation rates and how it affects the airflow pattern inside a space. The study was developed through Computational Fluid Dynamics simulation using Ansys software. Results showed an optimum flow pattern and increased velocities for solar collector inclination angles between 45° and 75° with the horizontal, for 28.4° latitude north. Maximum air velocity was obtained for 45° tilt.

Sakonidou et al (2008) developed a mathematical model, aiming to determine the solar collector's tilt that maximizes airflow inside a chimney. The analysis included theoretical predictions and an experimental model. The authors concluded that, when the inclination varies, two things occur in opposite directions: a lower inclination with the horizontal results in higher exposure to solar irradiation, but reduces stack heitght and, consequently, reduces effective pressure head of the chimney and so diminishes airflow. They obtained an optimum tilt between 65° and 76° for maximum airflow, and between 12 and 44° for maximum irradiation.

The objective of the presented research is to investigate a possibility to optimize solar irradiation on the solar collector of a solar chimney and also guarantee a considerable stack height, aiming to increase the system's performance in Brazilian's low latitude tropical climate. It consists in using a chimney extension, which would be responsible to maintain a minimum height for the solar chimney, independently from the absorber inclination, allowing the use of lower inclination angles for the solar collector. This is an important subject for designing solar chimneys in buildings located near the Equator region.

EXPERIMENT

An experimental study was developed through the construction of a test cell in the city of Sao Carlos, Sao Paulo state, Brazil (22° latitude south), under real weather conditions.

The test cell was built with ceramic bricks and had the following dimensions: 2.7m x 1.6m x 2.3m (Figure 2). The inlet opening was located 0.3m above the floor, at the south facade, with an effective open area of 0.14m^2.

The experimental chimney had a narrow parallelepiped shape solar collector of variable tilt, facing north, with dimensions: 1m length, 1m width and 0.18m air gap. The black absorber consisted of a 1mm thick aluminum sheet painted black and was provided with rectangular fins in the air passage (facing down), in order to increase the heat transfer between absorber and air, as recommended by Garg et al (1991). The absorber was covered with a 6mm thick clear glass. All exposed sides of the solar collector were insulated by a 5cm thick polyurethane layer (Figure 3).

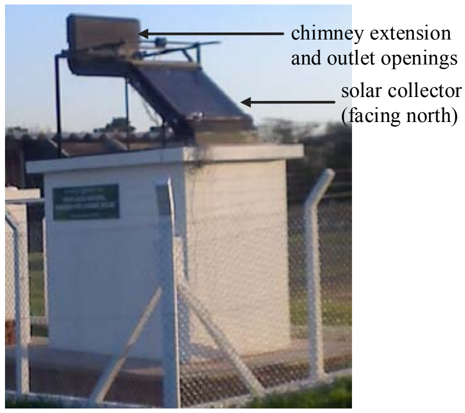


Figure 2 Experimental set-up of inclined solar chimney

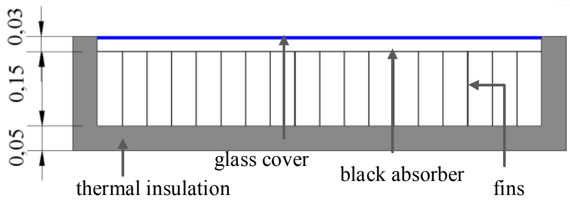


Figure 3 Cross section of the solar collector

With the intention of optimizing the solar radiation incidence angle on the glass cover throughout the year, the solar collector had an adjustable tilt, varying from 0° to 45° relative to the horizontal plane, covering the best range of angles for the current latitude. A chimney extension, made of black aluminum sheets, was used to maintain a 1.80m total height for the solar chimney, independently from the solar collector inclination. Outlet openings were located in both north and south facades, at the end of the chimney extension.

Contact-type sensors were used to measure surface temperatures in points located on the absorber surface, fin surface and inner surface of glazing. Hot-wire thermo-anemometers were used to measure air temperature and velocity inside the channel between absorber and glass and inside the channel between fins.

Outdoor weather data – including dry bulb temperature (DBT), relative humidity, wind velocity and direction, horizontal solar irradiation, pluviosity and atmospheric pressure – were obtained from the closest weather station of Brazilian's National Institute of Meteorology (INMET), situated 200m from the test cell location. Direct and diffuse solar irradiation were calculated from a recognized theoretical model, published by Muneer (2004).

According to the law of conservation of mass, it has been assumed that net volume flow rate through the solar chimney channel is given by stream velocity times the cross sectional area of the channel between absorber and glass added to stream velocity times the cross sectional area of the channel between fins.

Monitoring runned from March to August 2010. For each month, the solar collector inclination angle was changed, in order to be positioned at optimum tilt, according to solar altitude (Table 1). Data were registered each minute and, subsequently, hourly averages were calculated.

Table 1
Solar coordinates and optimum solar collector tilt – Sao Carlos, Brazil

Variable	Mar	Apr	May	Jun	Jul	Aug
Sunrise (h)	5:57	6:08	6:19	6:32	6:34	6:19
Sunset (h)	18:19	17:51	17:32	17:28	17:37	17:49
Solar declination angle (°)	-1.97	9.91	18.96	23.32	21.46	13.92
Solar altitude (°)	69.95	58.07	49.02	44.66	46.52	54.06
Optimum collector tilt (°)	20.05	31.93	40.98	45.34	43.48	35.94

SIMULATION MODEL CALIBRATION

Theoretical predictions of the solar chimney performance were developed through computer simulation, using AirflowNetwork calculation model of EnergyPlus software (version 6.0). In order to verify the results of the theoretical solution, a first computer simulation model was built to compare theoretical predictions against experimental measurements.

The comparison was performed for the period of 11th to 13th March 2010, with the solar collector at 20° inclination. The choice of this month among the collected experimental data was due to two important facts: it is summer season, period when natural ventilation for thermal comfort is most needed; and it is the month that presented the lower optimum inclination angle of the solar collector with the horizontal plane.

An EnergyPlus weather data file of the referred period was created using INMET weather data (Table 2). Since horizontal infrared radiation data is missing on the weather file, EnergyPlus calculates its intensity from the opaque sky cover field, by using an algorithm, which is fully described in the Engineering Reference document (2010).

The computer model had the same geometric and constructive characteristics as the experimental test cell, except that the fins inside the solar collector were not modelled, due to software limitations. Instead, the solar collector was composed by a simple box, where the black absorber had direct contact with thermal insulation (Figure 5). To account for local resistances existing in the experimental solar collector, pressure losses of the rectangular fins were calculated and added to the simulation model. Differences on solar absorption and thermal resistance due to the absence of fins were taken into consideration in the result analysis.

The software calculation is based on the assumption that the dissipation of heat into the flowing fluid is uniform and there is no temperature distribution of the flowing air normal to the chimney absorber and throughout the chimney height. Most part of the theoretical works on solar chimney performance are also based on these assumptions (Mathur et al, 2006; Sakonidou et al, 2008). Moreover, Chungloo and Limmeechokchai (2008) analyzed experimentaly this subject and obtained good agreement between temperature distribution along the air channel and the medium height.

Table 2
Summary of climatic data of Sao Carlos

Day (2010)	Maximum dry bulb temperature (°C)	Minimum dry bulb temperature (°C)	Maximum global irradiation (W/m^2)
11/03	29.7	17.3	966
12/03	30.8	18.0	994
13/03	30.8	19.0	957

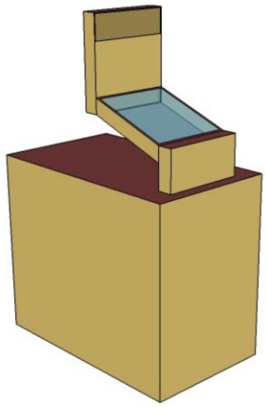
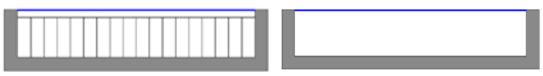


Figure 4 Computer simulation model



(a) Experiment *(b) Simulation model*
Figure 5 Solar collector

EnergyPlus offers three options of surface convection algorithm for inside surfaces and five options for outside surfaces. All options were tested and it was chosen the most proper options to solar chimney simulation, which were the Detailed algorithm for inside and the TARP (Thermal Analysis Research Program) algorithm for outside. The Detailed algorithm correlates the heat transfer coefficient to the surface orientation and the difference between the surface and zone air temperatures. It presents heat transfer equations for natural convection and for vertical, horizontal or inclined surfaces, facing up when heated or down when cooled. The TARP algorithm is based on the same assumptions as the interior Detailed model (EnergyPlus, 2010).

External wind pressure coefficients for inlet and outlet openings inputs were obtained through wind tunnel measurements, in tests developed at the National Laboratory of Civil Engineering (LNEC) of Lisbon, Portugal. The measurements were made in an open circuit wind tunnel, with a test chamber of 2m x 3m section, 9m length and variable speed up to 18m/s. Data were acquired for a 1:5 scale model and for the following wind directions: 0° (inlet opening at leeward), 45°, 90°, 120°, 120°, 150° and 180° (inlet opening at windward).

Figure 6 Wind tunnel tests

Wind tunnel measurements were taken considering an external barrier made by another test cell, existent in real conditions. Results of wind pressure coefficients are shown in Table 3.

Table 3
Wind pressure coefficients

Wind direction	Inlet opening – ambient	Outlet openings – chimney extension	
	Cp (south)	Cp (south)	Cp (north)
0°	-0.03	-0.48	0.67
45°	-0.14	-0.37	0.71
90°	-0.38	-0.14	-0.14
120°	0.22	1.07	-0.17
150°	0.39	0.66	-0.36
180°	0.24	0.39	-0.30

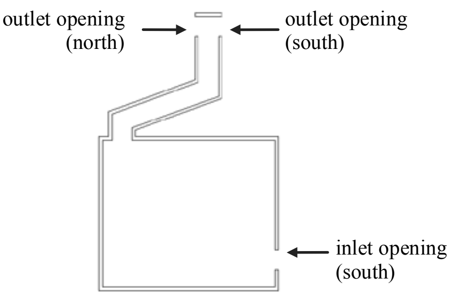


Figure 7 Wind pressure intakes location

Wind effects on a solar chimney is a complex subject, not yet presented in details by the current bibliography. The subject is being studied and will be object of a future paper.

Local resistances of the solar chimney channel were represented by the discharge coefficient (Cd), which was calculated through the mass flow equation, presented by Mathur et al (2006):

$$m = Cd.\rho_f.Ao\sqrt{\frac{2.g.\Delta h(Tf - Tr)}{(1 + Ar^2)Tr}} \qquad \text{(Eq. 1)}$$

Where:

m	Mass flow rate (kg/s)
Cd	Coefficient of discharge of the air channel
ρ_f	Density of air film between absorber and air (kg/m^3)
Ao	Outlet opening area (m^2)
Δh	Vertical distance between outlet and inlet (m)
Tf	Temperature of air channel (K)
Tr	Room temperature (K)
Ar	Ratio between outlet and inlet opening areas (Ao/Ai)

Input data for calculations, based on experimental monitoring, results on an average discharge coefficient of 0.12, representing the total pressure losses of the entire chimney channel, including resistances provided by the shutters of inlet and outlet openings, the fanfold articulations in curved sections and the rectangular fins of the solar collector, which were not present in the simulation model. This value was applied on a model pressure node.

SIMULATION ANALYSIS OF TILT VARIATION

After verifying the results obtained from the computer simulation, further analysis was developed aiming to investigate the performance of two geometrical configurations of solar chimney:

- The first consisting of a solar chimney positioned at the best inclination angle for maximum airflow, considering a balance between collection of solar radiation and stack height.
- The second consisting of a solar collector positioned at the best inclination angle for maximum solar irradiation, provided with a chimney extension to assure the maintenance of the same height difference between inlet and outlet as the first model. It is, basically, the same geometry of the experimental cell test, without fins.

This analysis was made based on the same location and weather data as the simulation calibration.

In order to identify the optimum tilt yielding maximum airflow for the first model configuration, calculations were made through computer simulation, testing chimney tilts between 10° and 75° and considering climatic conditions of Sao Carlos. Temperature differences between air channel and outdoors and height difference between inlet and outlet were analyzed to determine optimum thermal pressure gradient inside the chimney and, consequently, optimum airflow.

According to Marques da Silva (2003), Boussinesq approximation together with perfect gas law allow thermal pressure gradient between two points of different height to be approximately expressed as:

$$\Delta P^T \approx 0.0021.\Delta h.\Delta T \quad \text{(Eq. 2)}$$

Where:

ΔP^T Thermal pressure gradient (Pa)
Δh Vertical distance between outlet and inlet (m)
ΔT Temperature difference between air channel and outdoors

Air channel temperature varied between 17°C and 35°C, depending on the inclination angle and the hour of the day, while outdoor air temperature varied between 17°C and 28°C. The resultant optimum inclination angle for maximum airflow at Sao Carlos city is 50°, as shown by Figure 8.

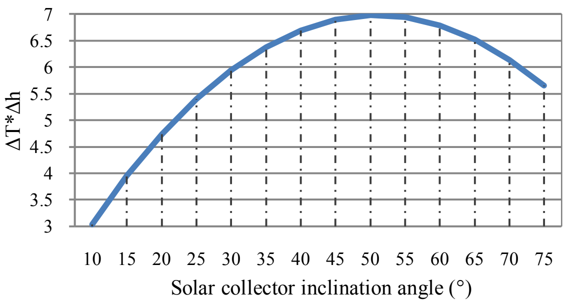
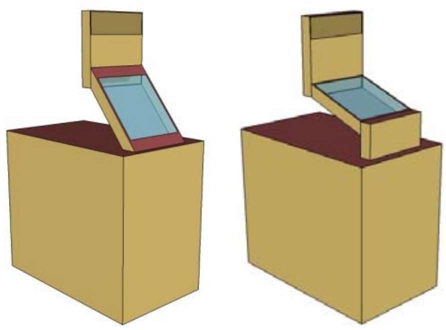


Figure 8 Optimum chimney tilt for maximum airflow

Therefore, the analyzed geometrical configurations had a 50° inclination angle chimney in the first model and a 20° inclination angle chimney in the second one. The models are presented in Figure 9:



(a) 50° tilt *(b) 20º tilt*
Figure 9 Solar chimney models

For simulation calibration, local resistances of the solar chimney were calculated based on experimental data. Since the experiment had many particularities that were not considered on the analysis of tilt variation (p. ex. shutters in inlet and outlet openings, rectangular fins in the solar collector, fanfold articulations in curved sections), in this analysis local resistances of air channels were calculated using pressure loss coefficients (ζ), evaluated using Idel'cik's (1999) procedures. The results obtained intended to be used as input data for computer simulations. The calculation consisted in the sum of pressure loss coefficients of straight and curved sections, taking into consideration the following input data:

Curved sections:

- Hydraulic diameter of the chimney, defined as (Idel'cik, 1999):

$$D_H = \frac{2.a.b}{a+b} \quad \text{(Eq. 3)}$$

Where:

D_H Hydraulic diameter of the chimney (m)
a Width of the chimney gap (m)
b Height of the chimney gap (m)

- Radius of the curved sections.

Straight sections:

- Ratio between width and height of the chimney section (a/b).
- Average Reynolds number. Experimental data were used to determine an interval for Reynolds number, which resulted between 1400 and 4000, varying between laminar and turbulent flow.

Resultant pressure loss coefficients varied between 1.62 (turbulent flow) and 2.41 (laminar flow) for 50° tilt chimney and between 2.07 (turbulent flow) and 3.24 (laminar flow) for 20° tilt chimney. Average values of 2.01 for 50° tilt and 2.66 for 20° tilt were used. These results were much lower than the one obtained in the experimental data, which was within expectations, considering the geometry simplification.

Results showed that pressure losses are an issue that should be given special attention, due to the fact that there is a significant effect of the chimney inclination angle on the pressure loss coefficient and, consequently, on the airflow penetration. According to Idel'cik (1999), the main reason for pressure losses in curved channels is the eddy formation near the inner wall of the tube (Figure 10), which tends to increase at smaller angles.

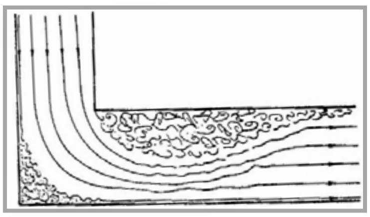


Figure 10 Airflow in a 90°curved tube – eddy formation (Idel'cik, 1999)

According to Bassiouny and Korah (2009), the optimum flow pattern and penetration depth can be seen for solar chimneys with inclination angles from 45° to 75°. Indeed, the 20° tilted solar chimney showed a higher flow resistance compared to the 50° tilted chimney, demonstrated by the pressure loss coefficient calculation.

RESULTS AND DISCUSSION

Comparison between simulation and experiment

This section presents the results used to compare the simulation model predictions to experimental measurements. Figure 11 compares the predicted glazing surface temperatures to measured values. Predictions agree well with experimental data, since the average difference between results was 1.2°C (1.3%).

Figure 12 compares predicted and measured absorber temperatures. The average difference between results was 4.4°C (8%), reaching 15°C around noon. Taking into consideration that the simulation model's absorber had no fins, it is reasonable to obtain higher temperatures for the predicted data, since the heat gained by the absorber is not being lost to the fins. Besides that, thermal insulation can be close to ideal in the simulation, but it can suffer damages in the experimental set up due to weather exposure, which affects the absorber heating.

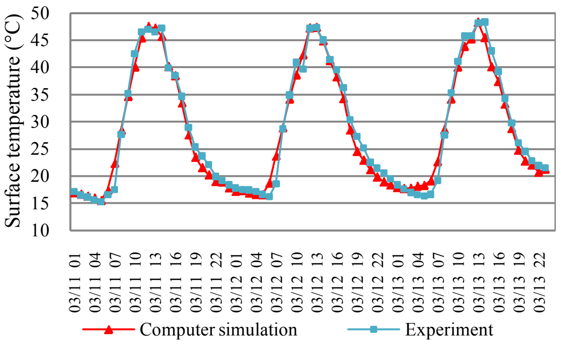


Figure 11 Glazing temperatures

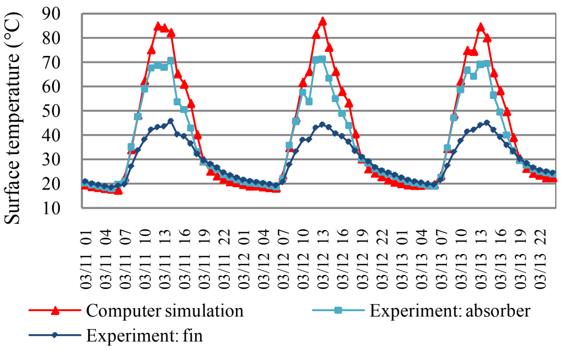


Figure 12 Absorber temperatures

Figure 13 compares the predicted air temperature to measured values in the channel between absorber and glass and in the channel between fins. Considering that the solar collector of the simulation model had no fins, there is a good agreement between predictions and measurement. Predicted values are close to the average between fin and absorber channels experimental measurements, the average difference between results being 1.1°C (1.4%).

Figure 14 shows a comparison between predicted and measured data for volumetric flow rate, allowing a direct evaluation of air change rate (ACH). Average airflow rates agree well, but there is a noticeable difference on rates of airflow variation during the day. This could be due to different thermal inertia and different thermal insulation performance between actual system and model. Numerical results presented in Table 4 (highlighted in Figure 14) show that computer simulation underestimate the results during morning and afternoon periods and overestimate during noon.

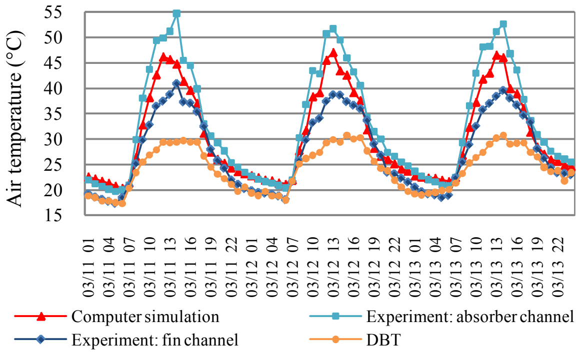


Figure 13 Air channel temperatures and DBT

Table 4
Volumetric flow rate – daylight period of March 11th

Hour (March 11th)	Experiment (m^3/h)	Simulation prediction (m^3/h)	Difference (%)
8:00	57.77	41.68	-39%
9:00	60.88	52.18	-17%
10:00	67.70	72.63	7%
11:00	62.36	84.60	26%
12:00	75.25	90.19	17%
13:00	71.77	95.07	25%
14:00	70.26	95.66	27%
15:00	74.61	60.18	-24%
16:00	93.60	73.87	-27%
17:00	79.85	67.68	-18%

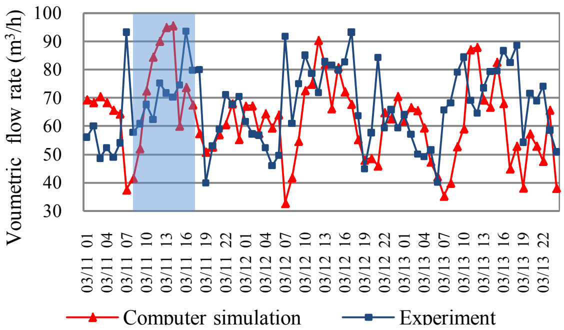


Figure 14 Voulmetric flow rate

It is also important to mention the measurement uncertainties originated from the monitoring system used in the experimental set up, especially the hot-wire anemometers, which can lead to differences between simulation and experimental results.

In spite of simulation and experiment uncertainties, it could be verified, from the simulation calibration against experimental data, that results presented a good agreement. In fact, computer simulation prediction has shown to be an appropriate tool for solar chimney performance evaluation, under similar conditions, provided that local resistances from the solar chimney channel and pressure loss coefficients are accurately predicted.

The experiment and wind tunnel analyses results showed a strong influence from winds on the solar chimney performance, either by enhancing as by reducing airflow. This subject is being studied in detail and will be object of a future paper.

Comparison between 50° and 20° tilted solar chimneys

This section presents the comparison of a solar chimney positioned at the best inclination angle for maximum airflow (50°tilt), with a solar chimney positioned at the best inclination angle for maximum solar irradiation (20° tilt). The second chimney has an extension, to assure the maintenance of the same height difference between inlet and outlet as the first model.

The results of solar radiation intensity on the solar collector planes are presented in Figure 15. The 20° tilted solar chimney glass cover has an exterior solar radiation incidence between 9% and 18% higher than the 50° tilted chimney, for the period from 8am to 6pm.

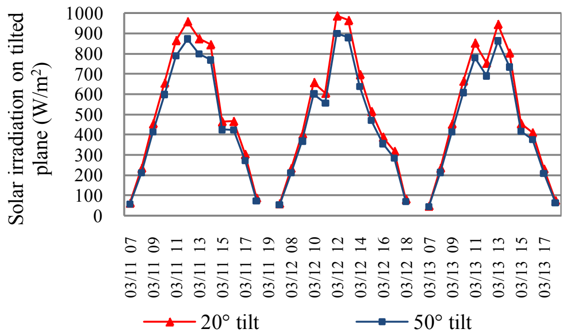


Figure 15 Solar irradiation on tilted plane – 20° and 50° tilts

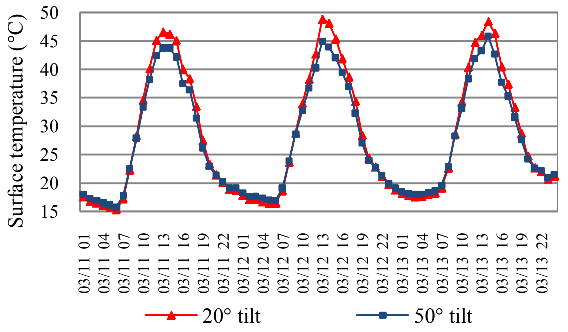


Figure 16 Glazing temperatures – 20° and 50° tilts

Figures 16 and 17 present glazing and absorber surface temperatures. The 20° tilted chimney has a glazing temperature on average 6% higher and an absorber temperature on average 9% higher than the 50° tilted model, for the period between 8am and 6pm.

Figure 18 presents air temperature in the chimney channel and outdoor dry bulb temperature. The air channel temperature of the 20° tilted solar chimney is, on average, 9% higher than the 50° tilted chimney.

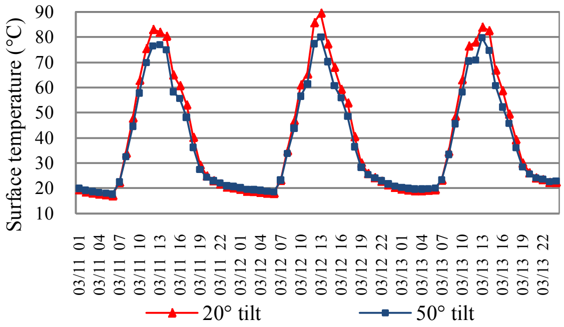


Figure 17 Absorber temperatures – 20° and 50° tilts

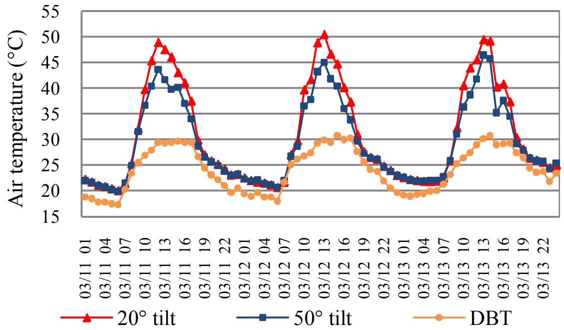


Figure 18 Air channel temperatures and DBT

The solar chimney's volumetric flow rate for both configurations was also predicted by computer simulation and is presented in Table 5 and Figure 19.

Table 5
Volumetric flow rate – daylight period of March 11th

Hour	50° tilt (m^3/h)	20° tilt (m^3/h)	Difference (%)
8:00	90.29	74.39	-21%
9:00	52.02	60.76	14%
10:00	49.54	60.81	19%
11:00	55.05	70.35	22%
12:00	54.99	75.37	27%
13:00	62.44	73.53	15%
14:00	67.67	71.59	5%
15:00	36.24	50.89	29%
16:00	47.18	56.89	17%
17:00	48.43	50.08	3%

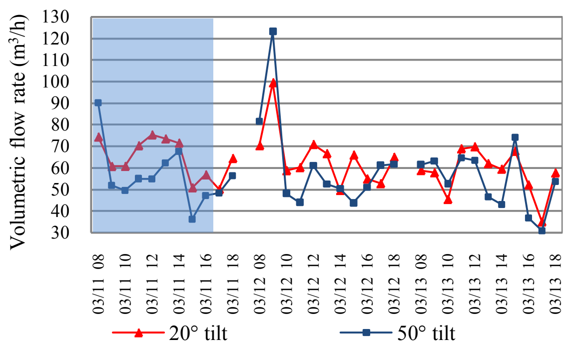


Figure 19 Volumetric flow rate – 20° and 50° tilts

Numerical results presented in Table 5 (highlighted in Figure 19) show that volumetric flow rate was higher, for most part of the day, on the 20° tilted solar chimney, compared with the 50° tilted chimney. For those hours with higher solar irradiation (between 11am and 1pm) the 20° tilted chimney performance, in volumetric flow rate, became 15% to 27% higher than the 50° tilted solar chimney.

By comparing results of volumetric flow rate (Figure 19) with results of solar irradiation on the tilted plane (Figure 15), it can be noticed that the solar chimney positioned at the best inclination angle for maximum solar irradiation (20° tilt) presented a better performance than the solar chimney at the best inclination angle for maximum airflow (50° tilt). The increase of 9% to 18% on exterior solar radiation incidence on the tilted plane of the 20° tilted solar chimney corresponded to an average increase of 6% to 14% on volumetric flow rate, reaching a 31% average rise at noon.

CONCLUSION

The present research aimed at investigating the performance of a solar chimney designed to obtain maximum solar irradiation and maximum airflow, intended to be used in a low latitude tropical climate city of Brazil, in low wind locations. The solar chimney design consists in a solar collector with optimum inclination angle in relation to solar irradiation, added to a chimney extension that assures a considerable stack height.

For low latitude locations, an absorber with less inclination captures more radiation, but compromises airflow rate due to the decrease of stack height. The theoretically determined results of this research demonstrated that using the proposed system – optimum inclination angle for maximum solar irradiation with chimney extension – effectively increased the performance of the solar chimney, enabling the use of solar collector with lower inclination angles.

Computer simulation prediction showed that the maximum daily volumetric flow rate of the proposed system was increased by 31%, comparing to a solar chimney with inclination angle calculated for maximum airflow. Furthermore, the hours of the day when natural ventilation is more required as a thermal comfort strategy inside buildings agrees with the higher airflow rates differences. However, the cooling strategy will be favorable only if indoor temperature is higher than outdoors, as mentioned before. A proper treatment of inlet openings – including vegetation, shading – is also favorable.

An important issue that works against the performance of the proposed system and should be carefully analyzed during the design process is the increasing pressure losses of curved sections in the system. Another important question to mention is the influence of winds on the solar chimney performance. This subject has not yet been studied in detail by the current literature and will be object of a future paper.

Moreover, simulation predictions are in satisfactory agreement with experimental results, which encourages its use for evaluating other design parameters and develop further comparative studies on solar chimneys.

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