IMPROVED MODEL FOR SOLAR CHIMNEY ANALYSIS

Christian Strobel, christian.s.strobel@gmail.com
Universidade Federal do Paraná – UFPR. C.P. 19011, Curitiba, PR – 81531-990, Brazil.

Luís Mauro Moura, luis.moura@pucpr.br
Viviana Cocco Mariani, viviana.mariani@pucpr.br
Pontifícia Universidade Católica do Paraná – PUCPR. Curitiba, PR – 80215-901, Brazil.

Abstract. *Solar chimneys are power generation plants which use the energy from the sun to promote airflow, and the kinetic energy is harnessed by turbines located at the base of the chimney which convert it into electrical energy. In this paper are proposed new approaches improving the mathematical models presented in the literature. The new approaches proposed include the influence of the multiple reflections of solar radiation on glazing collector and on glazing/ground interface in order to improve the accuracy of the total temperature increase by the system. Four models are analised, and the reasons for the difference among the models are highlighted. The proposed model in this study leads to an error of only 1.3% when compared to experimental data of Manzanares.*

Keywords*: Solar chimney, solar energy, renewable energy, heat transfer, solar tower.*

1. INTRODUCTION

Solar chimneys are power generation plants which use the energy from the sun to heat air as it enters a glass collector, and have a chimney installed at its center to promote a flow, by connecting the heated mass of air to a lower pressure region. The heated air has a lower density, and buoyancy forces arising from this mass promote the flow to the chimney outlet. This process creates a continuous airflow, and the kinetic energy is harnessed by turbines located at the base of the chimney which convert it into electrical energy. The ground below the chimney is a convenient way to store part of the day energy which is absorbed and releases this energy during the night, generating electricity continuously. The airflow created by the buoyant force is proportional to the increase in air temperature in the collector and the height of the chimney. The power is extracted by one or more turbines, similar to those used in hydroelectric power plants, where the static pressure is converted into mechanical work. The total power achieved is proportional to the volumetric flow rate and pressure drop across the turbine. Since this is a system that has little dependence on outside wind, which is intermittent, this type of plant becomes a very attractive development.

In 1981, an experimental solar chimney prototype with installed capacity of 50 kW and nominal height of 200 m was built in Manzanares, Spain, supported by the German government. Haaf et al. (1983) presented the details of operation, energy balances and cost analysis. Once implemented and with data acquired, Haaf (1984) presented preliminary results obtained by this prototype, which was in operation until 1989, and it demonstrated the feasibility and reliability of the concept of solar chimneys.

Due to this optimistic outlook after these studies conducted in Manzanares, an extensive literature has started to emerge, and studies with very different focuses have been conducted to determine the influence of several parameters on output energy and efficiency, as geometry of the plant, turbine disposal, quality of roof material, ground roughness and thermal properties, development and validation of mathematical and numerical models, as well the study of the technical and economic feasibility of implementing this kind of technology in several regions of the world.

Bernardes et al. (2003) presented a mathematical and numerical model to predict the power generation of a solar chimney. That model agrees with Manzanares data with a high degree; reaching a divergence of -2% to 1.5% depending on the simulation day. That model, due to the high level of agreement with the experimental data, is used in this study.

Koonsrisuk et al. (2010) proposed a different model from other works, which will also be discussed here in this work, in which the mass flow is determined by the sum of all pressure drops across the system, but does not consider all the losses involved, simplifying some minor losses such as the heat absorbed by the flow, and also does not consider the multiple reflections on the glass cover.

Thus, this study introduces several modifications in models from Bernardes et al. (2003) and Koonsrisuk et al. (2010) and comparisons between these models are made showing improvement in performance. Focusing on models, the original model of Bernardes et al. (2003) uses the heat transfer analysis in a semi-permanent scheme to predict the temperature increase and the momentum equation to determine the airflow velocity and the power output. The modified model of Bernardes et al. (2003), proposed in this study, uses the effects of multiple reflections on glass cover and on cover/ground interface, in order to improve the accuracy of the original model. The original model of Koonsrisuk et al. (2010) uses the pressure drops along the ground/collector, chimney and due the acceleration below the collector as the airflow moves to the chimney to predict the mass flow rate. That model do not consider the minor pressure drops, as well do not consider the absorption of heat on ground and cover. In particular, the modified model of Koonsrisuk et al. (2010), proposed in this study, includes other losses reported by Von Backström et al. (2006) and includes the use of the heat transfer analysis in a semi-permanent scheme to predict the temperature increase, considering the multiple reflections on the collector.

2. MATHEMATICAL MODEL

The proposed model considers mixed flow in an unsteady state and prescribed conditions for velocity fields where the working fluid is air. The flow velocity is a function of the buoyancy force caused by the increase of air temperature in the collector. This analysis must be cautious therefore, as there is the influence of the glass cover and the unsteady conduction in the ground. The figure 1 shows a schematic of the airflow in solar chimney.

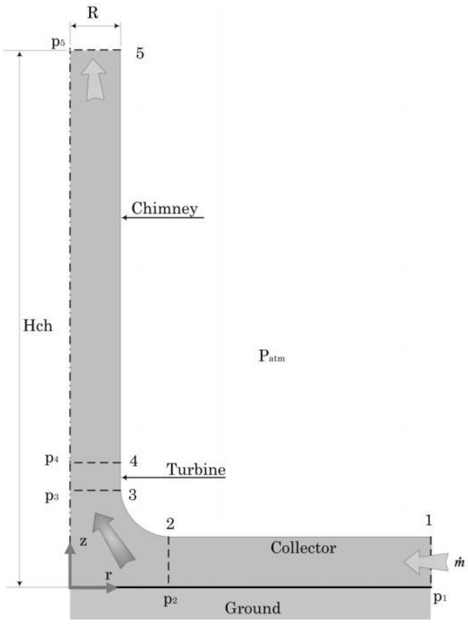

Figure 1. Schematic of the power plant model.

In order to investigate the behavior of the air inside the collector and the chimney, some assumptions must be set, including:

- The collector is treated as a plane surface;
- The height of the collector is set constant above a plane ground;
- The collector has a simple pane of glass;
- The airflow is axisymmetric, i.e., the uneven heat of collector surface related to chimney axis is neglected;
- The vertical temperature gradient between the ground and the glass cover can be neglected.

A solar chimney with a single collector, i.e. only with a glass coverage above the ground, has an energy flow as shown in figure 2.

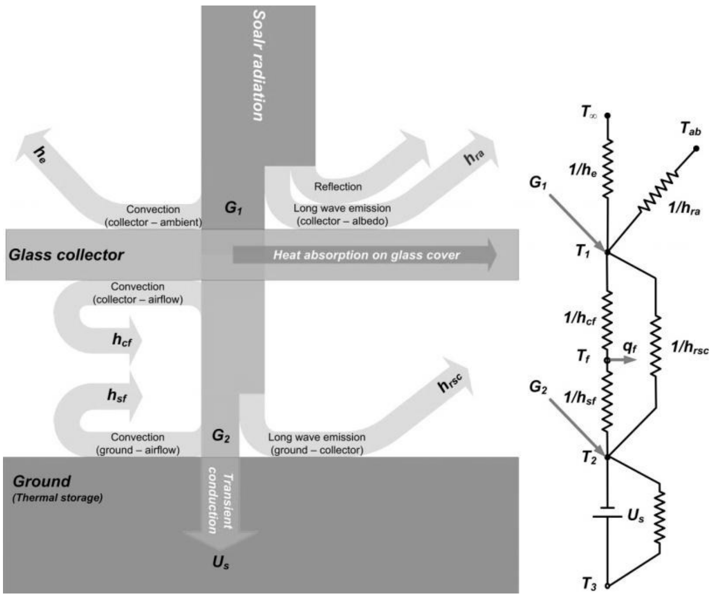

Figure 2. Thermal network on interface ground/collector and thermal resistances.

Each section can be analyzed individually, using the concept of thermal resistances, according to Bird et al. (1960). For each intermediate node an energy balance in steady state condition for a given time was made, as it is evident in the following equations:

$$T_1: G_1 + h_{rsc}(T_2 - T_1) + h_{cf}(T_f - T_1) = h_e(T_1 - T_\infty) + h_{ra}(T_1 - T_{ab}), \quad (1)$$

$$T_f: h_{cf}(T_1 - T_f) = h_{sf}(T_f - T_2) + q"_f \text{ e} \quad (2)$$

$$T_2: G_2 = h_{sf}(T_2 - T_f) + h_{rsc}(T_2 - T_1) + U_s(T_2 - T_3), \quad (3)$$

where

$$T_3 = T_{2,0}, \quad (4)$$

since $T_{2,0}$ is the surface temperature on the previous time step, and

$$U_e = h_e + h_{ra}. \quad (5)$$

Rearranging the terms the Eqs. (1) to (3) become:

$$T_1: (U_e + h_{cf} + h_{rsc})T_1 + (-h_{cf})T_f + (-h_{rsc})T_2 = G_1 + h_e T_\infty + h_{ra} T_{ab}, \quad (6)$$

$$T_f: (h_{cf})T_1 - \left(h_{cf} + h_{sf} + \frac{\dot{m}c_p}{\pi r L}\right) T_f + (h_{sf})T_2 = -\left(\frac{\dot{m}c_p}{\pi r L}\right) T_{f,e} \text{ and} \quad (7)$$

$$T_2: (-h_{rsc})T_1 + (-h_{sf})T_f + (h_{sf} + h_{rsc} + U_s)T_2 = G_2 + U_s T_{2,0}, \quad (8)$$

That could be written in a matricial form and the temperature array can be determined by matrix inversion.

Several convective and radiation heat transfer coefficients rely heavily on the temperature and properties of air and the environment. All these heat transfer coefficients are described in the work conducted by Bernardes et al. (2003) and are commonly found in literature. This scheme is used in all models in order to obtain the temperature profile.

The mathematical and numerical procedure of each model is extensive, and can be found easily in the literature. The description of each model is conducted as follows:

- Bernardes *et al.* (2003): uses a model based on the momentum equation to predict the velocity profile in the chimney, and process this information to predict the power output. The model considers only the transmittance of the glass cover, and ignores the multiple reflections on glass cover and on collector/ground interface.
- Bernardes *et al.* (2003) modified by this work: uses the same approach than the original model, but consider the influence of the multiple reflections on glass cover and on collector/ground interface. According to Strobel et al. (2007), the error induced by not using the appropriate methodology shown previously is about 1.5%. This may seem small, but it increases with multiple reflections between glass and ground. This work is the only one in current literature to treat the effect of multiple reflections in glasses coverage collector and on the interface ground/collector.
- Koonsrisuk *et al.* (2010): uses a model based on the sum of head losses along the system, and equals with the total pressure drop on the system. This models ignores secondary losses on the system, and simplifies the heat gain of the airflow as no heat losses occurs.
- Koonsrisuk *et al.* (2010) modified by this work: uses secondary losses proposed by Von Backström *et al.* (2006) and the correct heat losses along the system.

3. RESULTS AND DISCUSSIONS

Computational programs should provide the values of temperature, speed of air flow and power generated for each time step during a whole day. The chosen programming language was C++, which is widely used in scientific and technical matters. The complex equations do not have a closed analytic solution, so iterative resources must be used. In order to explore the capabilities of the computer to perform a large number of similar calculations in a relatively short time, the day was fractioned into smaller intervals of time steps, as well as the radius of the collector being divided into smaller sections in order to obtain a finite number of elements. This leads to a discontinuous approach, i.e. in semi-permanent scheme, with large number of identical operations, changing only the calculation parameters. The number of time steps, as well as the number of sections in the collector may not be very numerous because they increase the computation time. As the model will be validated based on Haaf's (1986) data obtained in experimental plant of Manzanares, and the same was instrumented to provide data every 600 seconds, this was the step time used.

The first step was to declare the physical constants and variables used by the program. The input data, such as thermo-physical properties of glass, ground and air, geographical conditions, dimensional characteristics and climatic conditions of the region should be provided. Climatic conditions in the form of hourly function must be entered, as well as estimated values as initial conditions of temperature and air velocity.

The first iteration phase consists of dividing the collector in a finite number of sections, and, starting from section furthest from the center, must be carried out the calculations of optical properties, properties of atmospheric air, mass flow, speed section, heat transfer coefficients and finally the calculation of temperatures for the section examined. To solve the gain temperature, an instant of time on the day of examination is set, at the point where the gain by solar radiation (approximately 6:00) starts, an arbitrary initial speed, as for example, 5 m/s, and considers that all surfaces are at the same temperature, as, for example, at atmospheric temperature.

This theoretical model assumes that for a small section, the temperatures of the boundaries around the air flow are uniform and airflow temperature varies linearly over the collector. The heat transfer coefficients are calculated with the initial data, and, after of each iteration recalculated for the final values for each iteration. After the analysis in the first section, the initial value for the temperature in the second section is the value found in the first section, and the temperature value for the entry of the fluid is the value obtained for the output of the first. The iterative process continues until the temperatures and the speed of air flow converges, reaching an error predetermined by the user. After this first series of iterations, the time step and change in the value of the incident radiation advances, and the iterative process is repeated, using the anterior time step values as initial guest. Note that the program runs for 7 equal days of simulation to exclude possible errors arising from the thermal inertia of the soil. A check is performed between the difference of the calculated temperature and the temperature of the previous iteration.

The properties of the ground, glass cover and geography for the region of Manzanares, in order to compare the mathematical models with the data obtained experimentally in Manzanares, are shown in table 1.

Table 1: Simulation parameters for Manzanares pilot plant.

Parameter	**Value**	**Units**
Collector height	4.0	m
Collector diameter	244.0	m
Chimney diameter	10.0	m
Chimney height	194.0	m
Glass extinction coefficient	32.0	m^{-1}
Ground and glass cover emissivity	0.9	-
Thermal conductivity of ground	0.6	$W.m^{-1}.K^{-1}$
Thermal diffusivity of ground	$2.91x10^{-7}$	$m^2.s^{-1}$
Factor of pressure drop on turbine	0.8	-
Location	Manzanares	-
Latitude / Longitude	39.03 (North) / 3.14 (West)	°
Date	06/08/1987	-
Maximum error	0.01	%
Number of sections	5000	-
Time step	600	s

The experimental data obtained in 1987 by Manzanares team was sent by Weinrebe (2010) in a personal letter to the authors. This data is of extreme importance to the proposal of this work, given the need for validation and comparison of the models treated in this work with experimental data. In addition, the input data of temperature, horizontal global solar radiation, relative humidity and the ambient air velocity were also provided.

The power for the Koonsrisuk et al. (2010) model was much higher than expected, in the order of 200%, as shown in Figure 3 and the values in Table 2. This is explained by the several head losses not being considered, as mentioned before. Modified Koonsrisuk et al. (2010) model has a smaller increase, but also higher than expected, as shown in Figure 3 and the values in Table 2, with an error of 37.4%, due to other smaller head losses still not being taken into account, and there is no work in the literature that provides these minor losses for this application. One is the head loss on the structure that supports the glass collector, which generates a drop in pressure. A future work must be carried out to predict the drag in each pillar, and consequently the head loss in it.

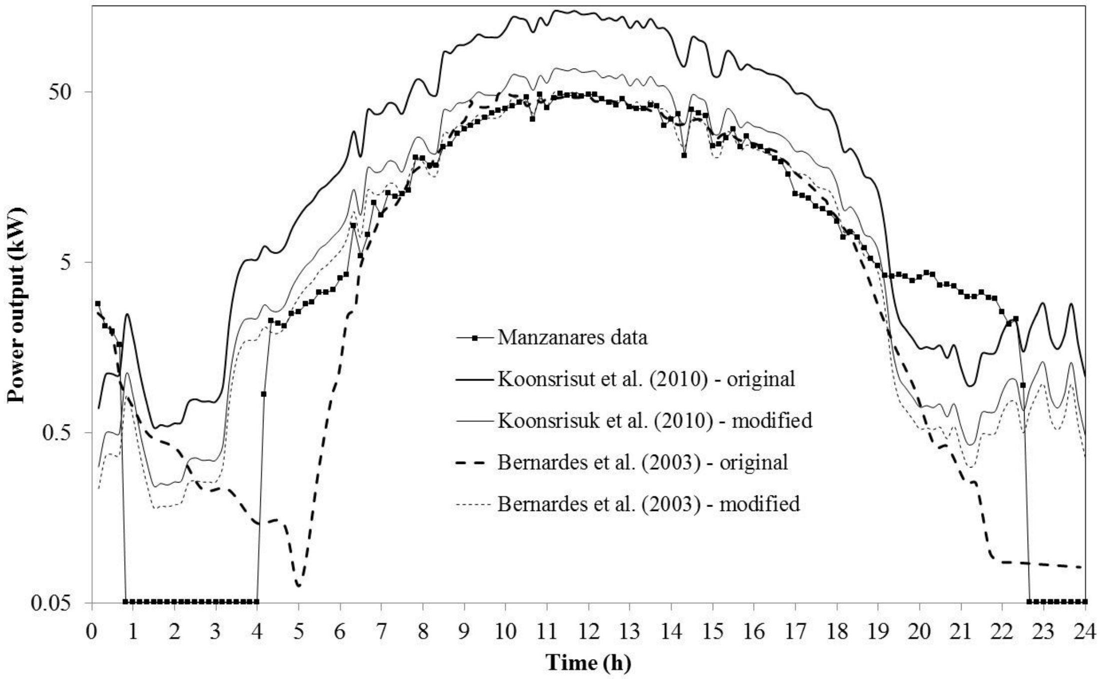

Figure 3. Power output for each model.

Table 2: Results for power output of each model.

Method	Energy output (kWh)	Divergence (%)
Manzanares	366.80	(Standard value)
Bernardes et al. (2003) – Original	360.70	-1.6
Bernardes et al. (2003) – Modified	370.52	1.0
Koonsrisuk et al. (2010) – Original	1102.09	200.4
Koonsrisuk et al. (2010) – Modified	504.51	37.5

Despite both models of Koonsrisuk et al. (2010), original and modified, the model proposed by Bernardes et al. (2003) obtained a very good approximation to the experimental results of Manzanares, which justifies the use of the model with a good fit, as can be seen in Figure 3 and its values in Table 2, leading to an error of only -1.6%. The modified model of Bernardes et al. (2003), using optical properties that consider the effects of multiple reflections in glass cover material and glass/ground interface, led to even more accurate results, as can be seen in Figure 3 and Table 2, generating an error of 1.3%.

Both models of Koonsrisuk et al. (2010) are interesting, but deserve a more in-depth study of all the variables involved, which as of yet are still not fully addressed by the literature. The model of Bernardes, original and modified, delivers more reliable results for estimating the power generation, with a divergence from the experimental model of Manzanares in the order of -1.6% and 1.3% respectively.

Note that there is no data obtained on the uncertainties of measurements performed in Manzanares. Therefore, the hypothesis from the measured results from Manzanares team are considered correct, and this work considers those data to be standard results.

4. CONCLUSION

This paper proposed the mathematical models analyses of Bernardes et al. (2003) and Konsrisuk et al. (2010) comparing them with the experimental prototype of Manzanares, in addition to two other models, based on the former two, and modified in this work to verify improvement points and convergence in the results. Despite the original and modified models of Bernardes et al. (2003) having a very small margin of error, to the order of -1.6% and 1.3%, respectively, and of original and modified Koonsrisuk et al. (2010) models having a much larger discrepancy in the order of 200.4% and 37.4%, respectively, this does not mean that the work of Koonsrisuk should be ignored. On the contrary, it means that a new approach was launched by the authors, leaving a margin for future studies on pressure drops in this type of structure, so as to improve the models accuracy.

5. REFERENCES

Baehr, H.D., Stephan, K., 1996. Wärme und stoffübertragung, Springer-Verlag, Berlin.

Bejan, A., 1984. Convection Heat Transfer, John Wiley & Sons, New York.

Berdahl, P., Martin, M., 1984. "Emissivity of clear skies". Solar Energy, vol. 32, pp. 663-664.

Bernardes, M.A.d.S., Weinrebe, G., Voβ, A., 2003. "Thermal and technical analyses of solar chimneys". Solar Energy, vol. 75, pp. 511-524.

Bird, R.B., Stewart, W.E., Lightfoot, E.N., 1960. Transport Phenomena, John Wiley & Sons, New York.

Carslaw, H.S., Jaeger, J.C., 1996. Conduction of Heat in Solids, Oxford Science Publications, Second Edition, Oxford University Press.

Chen, R.Y., 1973. "Flow in the entrance region at low Reynolds numbers". Journal of Fluids Engineering, vol. 95, pp. 153-158.

Gnielinski, V., 1976. "New equations for heat and mass transfer in turbulent pipe and channel flow". International chemical engineering, vol. 16, pp. 359-368.

Haaf, W., 1984. "Solar chimneys. Part 2: Preliminary test results from the Manzanares pilot plant". International Journal of Solar Energy, vol. 2, pp. 141-161.

Haaf, W., Friederich, K., Mayr, G., Schlaich, J., 1983. "Solar chimneys. Part 1: Principle and construction of the pilot plant in Manzanares". International Journal of Solar Energy, vol. 2, pp. 3-20.

Hedderwick, R.A., 2001. Performance evaluation of a solar chimney power plant. Department of mechanical engineering. University of Stellenbosch. Master dissertation, South Africa.

Koonsrisuk, A., Lorente, S., Bejan, A., 2010. "Constructal solar chimney configuration". International Journal of Heat and Mass Transfer, vol. 53, pp. 327-333.

Siegel, R., Howell, J.R., 1992. Thermal Radiation Heat Transfer, Hemisphere Publishing Corporation, Third Edition, New York.

Strobel, C.S., Mendes, N., Abadie, M.O., 2007. "Absorption of solar radiation in thick and multilayered glazing". Proceedings of the BS 2007, Beijing, pp. 1-8

Von Backström, T.W., Kirstein, C.F., Pillay, L.A., 2006. "The influence of some secondary effects on solar chimney power plant performance". R&D Journal, vol. 22, pp. 5-10.

Weinrebe, G., 2010. Personal letter to author. Schlaich Bergermann Solar GmbH. Stuttgart, Germany.

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