INTEGRATED MODEL OF A SOLAR CHIMNEY EQUIPPED WITH AXIAL TURBINES

Integrated model of a solar chimney Equipped with axial turbines

Daniele Fiaschi[a], Giampaolo Manfrida[b], Lorenzo Talluri[c]

[a] *Dipartimento di Ingegneria Industriale, Università di Firenze, Firenze, Italy, Daniele.Fiaschi@unifi.it*
[b] *Dipartimento di Ingegneria Industriale, Università di Firenze, Firenze, Italy, Giampaolo.Manfrida@unifi.it*
[c] *Dipartimento di Ingegneria Industriale, Università di Firenze, Firenze, Italy, Lorenzo.Talluri@unifi.it*

Abstract:

Solar chimneys are large devices which are becoming frequently proposed in new energy systems. The early prototypes (Manzanares) have demonstrated a potential for improvements with increasing size and height. The new trends in tall buildings technology allow to reach tower heights exceeding 1000m, so that the idea of integrating a solar chimney in a tall building is attracting the attention of architects, building designers and real estate investment companies. Model of solar chimneys can be found in the literature; also, the fundamentals of the design of turbines to handle the large volumetric flows have been investigated by some researchers. In practice, however, the system composed of tower and turbine should be investigated together, because the turbine design determines its characteristic curve, and the solar chimney/turbine system is operated in variable conditions over the year, thereby changing both the buoyancy effects in the tower, and the operating conditions of the turbine. The model applied is a simple buoyancy-driven flow model for the tower; for the turbine, once the sizing has been performed considering the design operating conditions, a simplified off-design model is applied to predict the turbine losses and efficiency, considering the full characteristic curve in terms of resistance versus flow rate. The overall model allows to investigate parametrically the relevance of the fundamental design variables (such as degree of reaction, flow and work coefficient for the turbine; tower height and diameter) and the sensitivity to variable daily meteorological conditions.

Keywords:

Solar Chimney. Axial Turbine.

1. The attractiveness of Solar Chimneys

Solar Chimneys (SC) are relatively simple devices, working on the basic principle of inducing a draft by means of naturally buoyant flows. After the original ideas by Cabanyes (1903) and Günther (1931) [1], the idea has become feasible because of advances in structural engineering, and this lead to the design and construction in 1980 of the first significant-scale (50 kW nominal) prototype in Manzanares [2, 3]. The development of large Solar Chimneys requires tower heights as large as 1000-1500 m; although this may seem a very hard challenge, these heights have been nearly reached for most recent skyscrapers, and should be possible in the near future for a dedicated (power conversion) design. The growth in size allows a considerable decrease in the production cost of electricity, with an expected value of about 0,1 €/kWh and a capital cost of 10000 €/kWp (this figure is based on a 100 MWe unit, with a tower about 1000m high having a diameter of about 110 m [4]); moreover, SCs have low maintenance costs and a very long lifespan is projected. The environmental performance of solar chimneys is potentially superior to that of most other renewable energy conversion systems (a value of 10 g of CO2 per kWh is reported in [1]). This makes them attractive for the future development of renewable energy. The main challenge is still the structural design of the tower, with large safety margins imposed by the lack of knowledge on the full-scale dynamic effects of wind action at heights exceeding 1000 m.

2. Models for the performance of Solar Chimneys

Solar Chimneys (Figure 1) are energy conversion devices based on the development of a buoyant flow inside the draft tower; this flow is determined by heating of air across the solar collector section. Work extraction devices (typically, a set of turbines) are installed inside the tower to produce power from the heated air stream. As for all solar energy conversion systems, the power produced is highly influenced by the available radiation, which is subject to the natural daily and seasonal cycle, and presents a stochastic nature which depends considerably on the local climate.

Relevant literature is available on the design of Solar Chimneys; apart of the several structural models considering the unsteady effects of wind (which are very important for future development, [1, 2]), thermodynamic models of the SC have been developed [5, 6, 7]. Most of them treat with considerable accuracy the heat transfer across the collector section [6, 7, 9, 10, 12]; exergy analysis has also been applied [8, 13] as well as computational fluid dynamics [11, 16, 17]. The fundamentals of turbine design, focusing on the axial solution (suitable for large flow rates and small enthalpy and pressure drops) are examined in [13, 14].

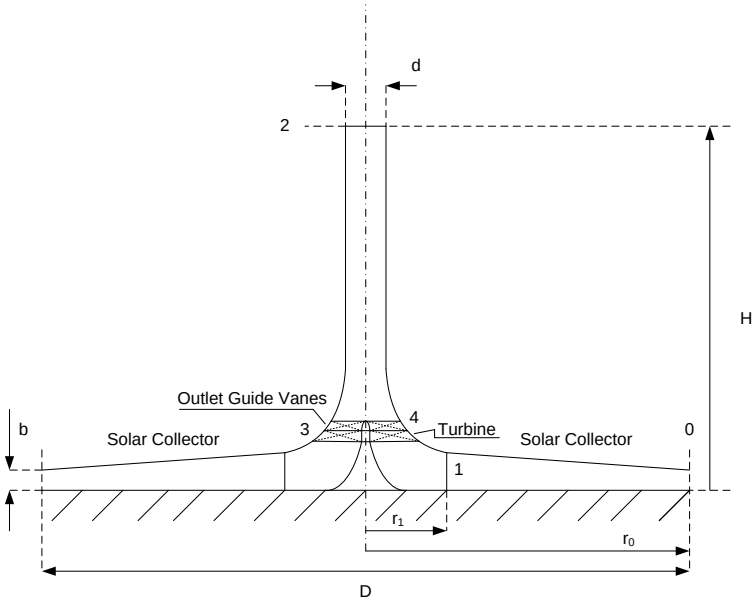

Fig. 1. Sketch of a Solar Chimney.

Most of the attention of the researchers is focused on design guidelines: however, it appears that reliable models capable of predicting the year-round performance of a given SC have not been developed. This appears to be very important from several point of views, namely:

- The nature of solar radiation is time-dependent, with typical daily and seasonal cycles; consequently, a SC is seldom operated at its nominal design conditions
- In order to obtain a reliable calculation of the economics, the design data are relevant for estimating the capital and maintenance costs; however, the final costs of energy (€/kWh), as well as the environmental performance (e.g., g_{CO2}/kWh) need to be calculated with reference to an year-round operation
- The flow rate across the tower should be estimated by means by a simulation of the performance of the solar collector, coupled to a turbine model capable of predicting the turbine pressure drop as well as its efficiency

From the technical literature, it appears that coupling of the SC/turbine models has only been performed considering the characteristic curve of the turbine [6] (which allows to calculate the turbine pressure drop given the flow rate), usually extending general, non-dimensional curves; or implementing improved correlations for the turbine inlet loss [9]; in all these cases, the turbine efficiency is considered constant.

3. Coupled model of the Solar Chimney and turbine

The purpose of the present work is to develop a fully-coupled model of the solar chimney (including the collector section) and of the turbine, operated in the normal, fixed-speed mode. The complete model is divided in the following in three sections: the solar collector, the turbine (design and off-design), and the tower/system assembly.

3.1. Model of the solar collector

The model of the solar collector applies the fundamental guidelines of [18], considering the absorbance and transmissivity of the glass cover; the greenhouse effect on the inner side is modelled considering mutual radiation exchange between the inner side of the cover and the ground; convection effects are included (outside air and inside channel); the ground is modelled as a linear conductive layer leading to a constant temperature value at a depth of 10m. The model is implemented as a set of equivalent resistances, using a simplified approach similar to the one described in [19].

The global radiation is the sum of the beam and diffuse components:

$$G = G_b + G_d \quad (1)$$

The collector is set horizontally so that no correction should be done for tilt and ground reflectance.

Figure 2 is a schematic of how the solar radiation is transferred across the collector.

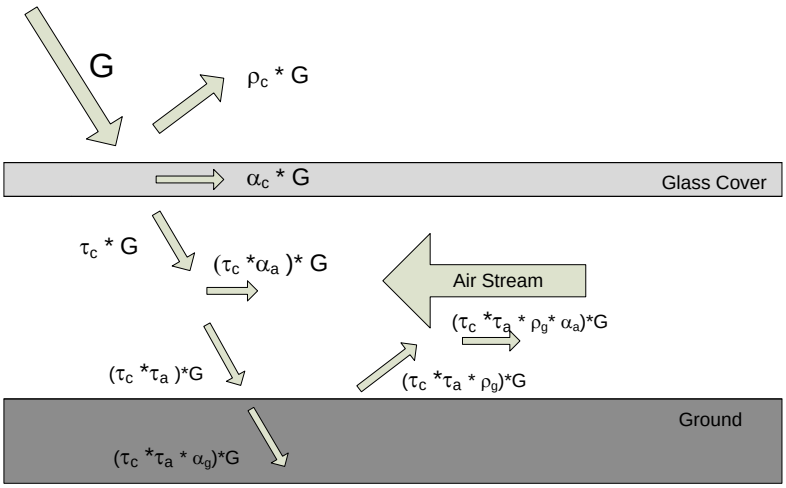

Fig. 2. Schematic of solar radiation transfer process.

Table 1 reports the fundamental data assumed for the heat transfer properties. Air is treated as a fully transparent medium, that is, $\alpha_a = 0$, $\tau_a=1$; heat transfer to air takes place only by means of convection.

Table 1. Solar collector design variables

Variable	Value
α_a	0
α_c	0,05
α_g	0,9
ε_c	0,05
ρ_c	0,05
ρ_g	0,1
τ_c	0,9

Under these assumptions, the radiation flux on the ground is given by:

$$G_g = \tau_c \alpha_g \, G \quad (2)$$

Figure 3 is a sketch of the general scheme applied for the calculation of heat transfer (radiation, convection and conduction).

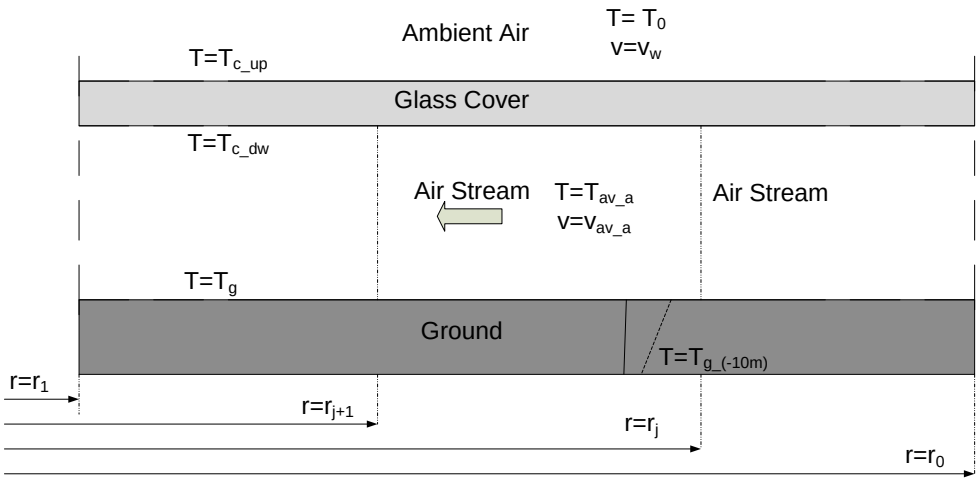

Fig. 3. General schematic of solar collector heat transfer.

For external heat transfer, forced or natural convection correlations for fluid flow over an horizontal surface are applied [20, 21]; moreover, radiation from the glass cover to the sky was considered with $T_{sky} = T_0 - 8$ and the emissivity of the glass cover $\varepsilon_c = \alpha_c$. The scheme represented in Fig. 3 is solved through an equivalent representation of a thermal resistance network, represented in Figure 4; the solution is applied proceeding from the inlet section 0 to the solar collector outlet 1.

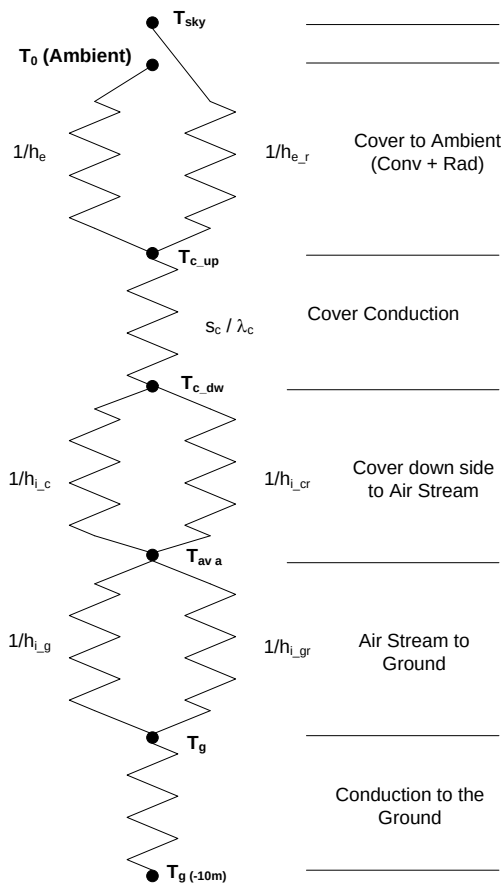

Fig. 4. Equivalent thermal resistance network for the solar collector.

The energy balance for the j-the section is written as:

$$\dot{m}\, c_p\left(T_{a,j+1} - T_{a,j}\right) = \pi\left(G + q_{up} + q_{dw} - q_{irr}\right)\left(r_j^2 - r_{j+1}^2\right) \quad (3)$$

$$q_{dw} = h_g\left(T_{g\_j} - T_{av\_a\_j}\right) \quad (4)$$

$$q_{up} = h_c\left(T_{c\_dw\_j} - T_{av\_a\_j}\right) \quad (5)$$

$$q_{irr} = \varepsilon_c\, \sigma\left(T_{g\_j}^4 - T_{c\_dw\_j}^4\right) \quad (6)$$

The values of the heat transfer coefficients h_c and h_g were calculated using the internal procedures for pipe flow available in [21]. The set of equations (3-6) allow to calculate the temperature increase ($T_1 - T_0$) = $T_{a,n} - T_{a,0}$ once the mass flow rate is known. Knowledge of the flow rate depends on the pressure loss characterization of the whole circuit, composed of: tower, turbine and solar collector. For this last, a simplified approach for the friction coefficient was adopted, applying the well-known formula of Colebrook:

$$1\Big/\sqrt{f_{sc}} = -2\, log_{10}\left[\left(\frac{\delta}{3{,}7D_h}\right) + \frac{2{,}51}{\left(Re\sqrt{f_{sc}}\right)}\right] \quad (7)$$

3.3. Model of the turbine

The design of the turbine has strong drawbacks on the whole system performance. Detailed guidelines can be found in [22], analysing the fundamentals of turbine design in terms of non-dimensional variables Φ, Ψ, and DR.

$$\Phi = \frac{v_{ax}}{u} \quad (8)$$

$$\Psi = \frac{\Delta h}{u^2} \quad (9)$$

$$DR = \frac{\Delta h_{rot}}{\Delta h_{st}} \quad (10)$$

In the present case, the simple and well-established correlation of Soderberg [23] was applied to calculate the stator and rotor losses, solving for the complete velocity triangles, flow angles and total-to-static efficiency. Figures 5 (a) and (b) examine the sensitivity of design to the Degree of Reaction and Load Coefficient.

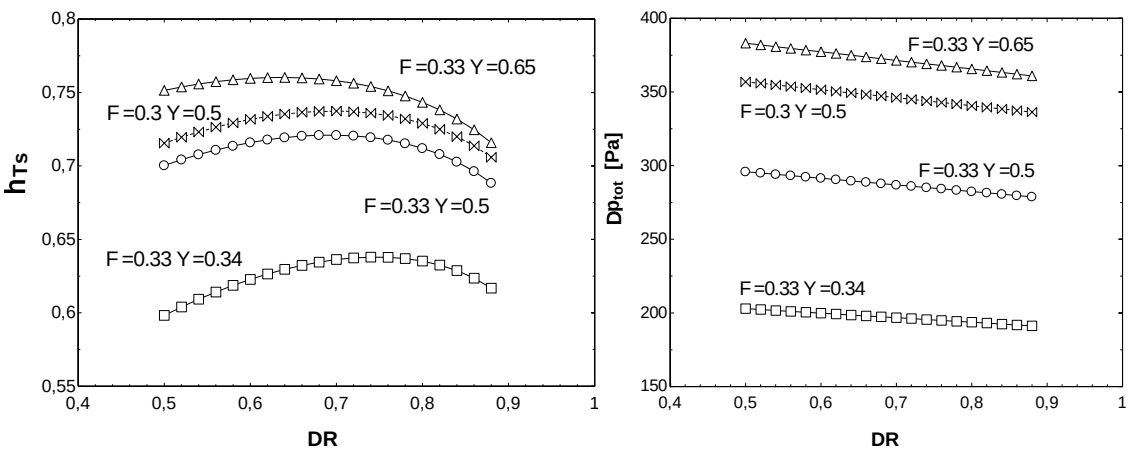

Fig. 5. Effect of DR and Ψ (Φ = 0,33): (a) Efficiency (b) Pressure drop

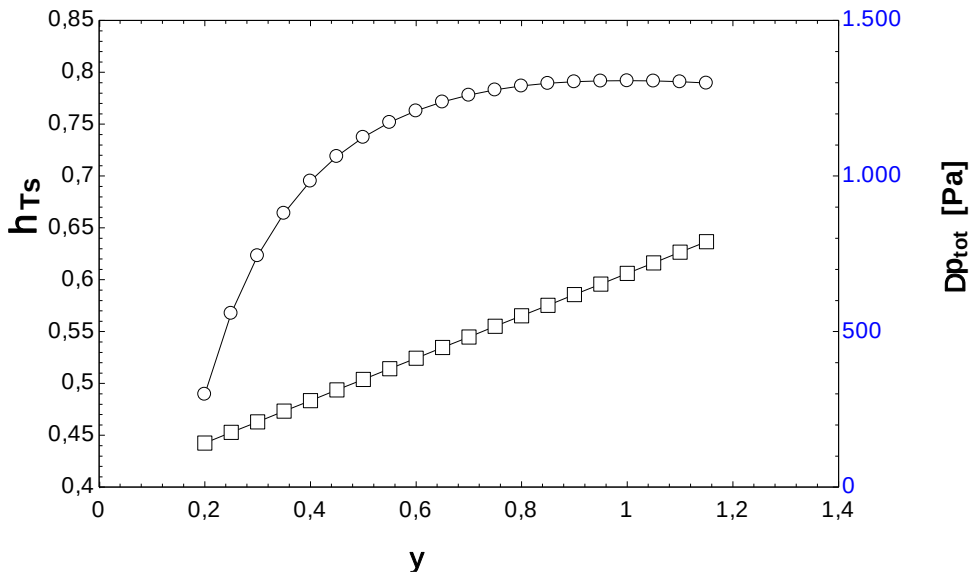

Fig. 6. Effect of load Coefficient Ψ (DR = 0,7; Φ = 0,3): Efficiency and Pressure drop

As expected (Figure 6), optimization in terms of Load Coefficient can be achieved for Ψ ≅ 0,98; however, this would lead to very high turbine pressure drops, which could be justified only for very tall solar chimneys (also the tower and solar collector pressure drops must be added). In any case, it makes little sense to pursue extreme values of turbine efficiency (leading to high load coefficients), sacrificing the collector performance (which is strongly affected by the flow rate and by the sizing of the collector field). Consequently, a relatively low value of Ψ is usually selected. Figure 7 examines the sensitivity of the turbine design to the Flow Coefficient Φ; considering these constraints, the design set of non-dimensional variables was chosen at DR = 0,7; Φ = 0,33; Ψ = 0,38; the resulting calculated value of η_{ts} at design conditions was about 0,67.

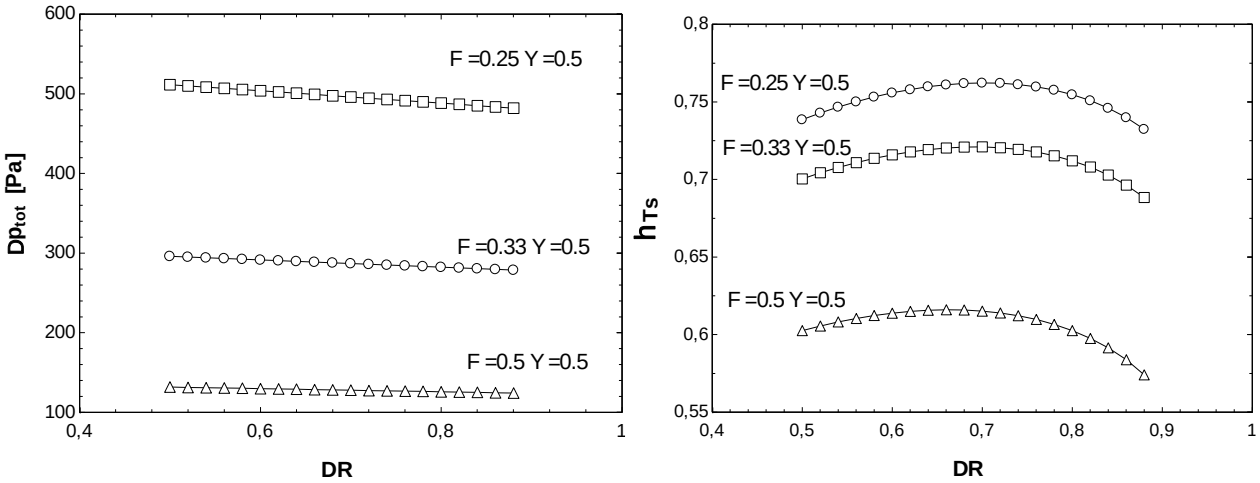

Fig. 7. Effect of DR and Φ (Ψ = 0,5): (a) Efficiency (b) Pressure drop

In order to estimate the performance of the axial-flow turbine under off-design conditions, the simplified correlation proposed by Latimer [24] was adopted. The original data were correlated and fitted with an approximating polynomial, resulting in the functional dependence shown in Figure 8. In practice, working on the turbine non-dimensional characteristic curve Ψ=f(Φ) the value of the turbine efficiency can be adjusted applying the correction for the input value of the ratio Ψ/Ψ_d.

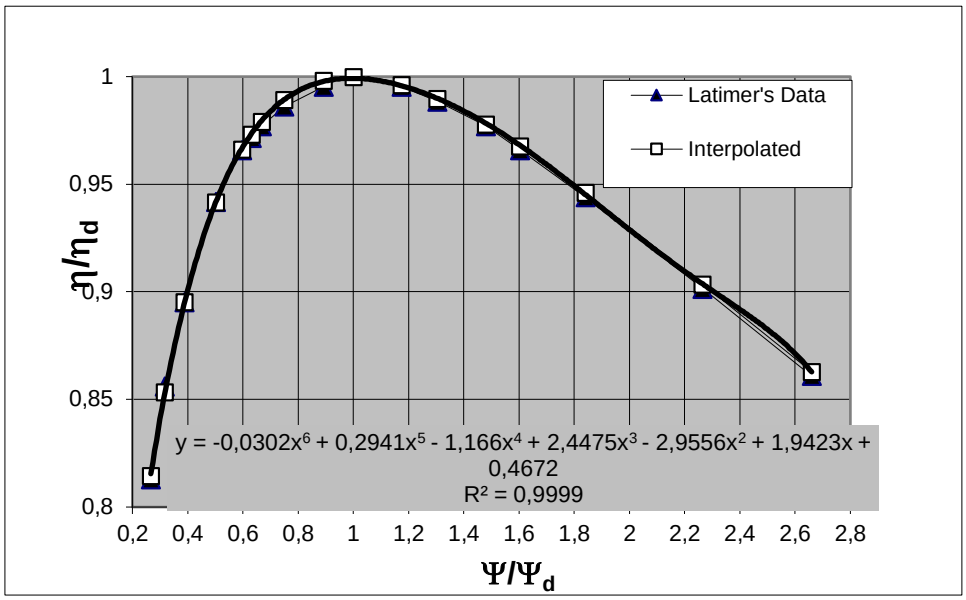

Fig. 8. Off-design Efficiency correlation (adapted from [24])

3.3. Tower – System Assembly

The tower is modeled as a circular channel with incompressible flow. The energy equation between the inlet/outlet sections is written as:

$$\frac{v_2^2}{2} + gH + \frac{p_2 - p_0}{\rho_{av}} + W - Q + R = 0 \qquad (11)$$

Again, the friction losses along the tower are calculated by (7); the heat loss is evaluated considering internal and external convection and conduction across the structural material.

Equation 11, together with the calculation of the overall resistance R (solar collector + tower + turbine) and with Euler's equation for turbine work, provides the solution in terms of the outlet velocity v_2; this last determines the flow rate as

$$\dot{m} = \rho_2 \, v_2 \, A_2 \qquad (12)$$

The power is determined from the turbine model as:

$$W = \dot{m} \, \Delta h_o = \dot{m} \;\; \eta_{ts} \; \Psi \, u^2 \qquad (13)$$

considering that $\eta_{ts} = f\,(\Psi/\Psi_d) = f_1(\Phi/\Phi_d) = f_2(\dot{m}\,/\dot{m}_d)$.

4. Preliminary results

At the present development stage, the model is run for typical daily simulations (a preliminary design study). The model was applied on available data from the Manzanares plant [2, 25]. The main data for the reference case are resumed in Table 2. Meteorological data from Caceres, SP were assumed, for a reference day of July.

Table 2 –Manzanares reference case

Input data	
Tower height, m	195
Tower Diameter, m	10
Collector Diameter, m	244
Collector channel height, m	1,85
Reference Case - Calculated values - Design	
Flow rate, kg/s	480
Power Output, kW	76
Turbine inlet velocity, m/s	7,5
Turbine pressure drop, Pa	218

Table 2 cannot represent a point-by-point comparison with the experimental results, as the turbine design is completely different from the prototype; however, the values of the turbine inlet velocity are close to those documented in [25].

Fig. 9 shows the trend of efficiencies of the collector and of the turbine over a reference day in July. It is clear that the performance of the collector is optimized around noon; the turbine operates largely at over-design, however its performance is not severely hindered and achieves its maximum under relatively low radiation conditions in the morning and afternoon, thereby compensating to some extent for the lower performance of the collector assembly. Both efficiencies are affected by the flow rate. On the reference day of July, the SC would be able to produce about 650 kWh. The time history of the turbine and system performance non-dimensional indicators is resumed in Figure 10. The relevance of the off-design operation is made evident by the wide excursion of the ratios Φ/Φ_d and Ψ/Ψ_d over the day. The power is proportional to the product of the two, so that the result is that $0{,}25 < W/W_d < 1{,}15$.

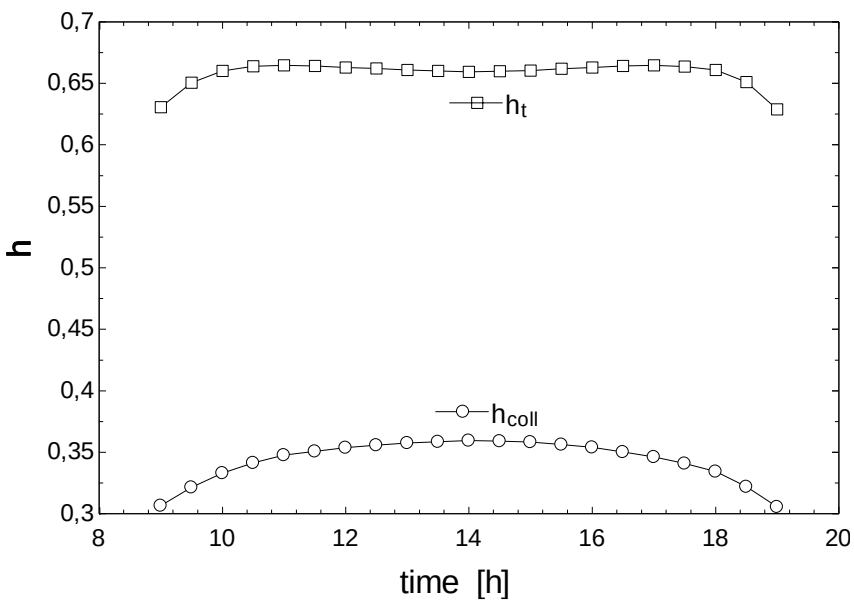

Fig. 9. Daily trends of efficiencies: (a) collector (b) turbine (reference day in July)

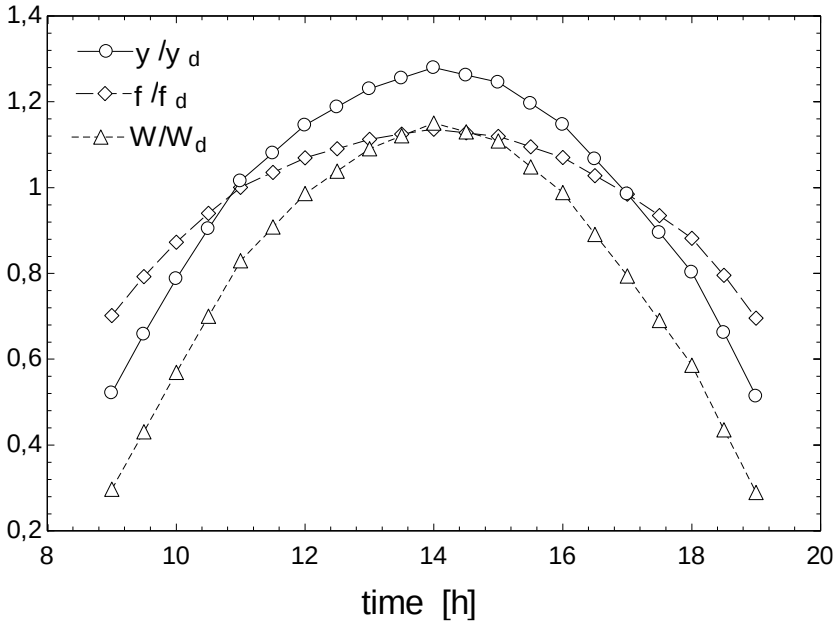

Fig. 10. Time history of Φ, Ψ, and non-dimensional power (reference day in July)

The model has then be applied to an up-scaled case of a tower with H = 1000m, whose main data are resumed in Table 3. The performance parameters (efficiencies, non-dimensional indicators) have daily trends similar to those represented in Figs. 9 and 10 (with different values and wider excursion of the non-dimensional parameters). The large SC would be able - on the same reference day of July and location - to produce about 29000 kWh.

Table 3 – Up-scaled (H = 1000 m) case

Input data	
Tower height, m	1000
Tower Diameter, m	25
Collector Diameter, m	610
Collector channel height, m	2,1
Up-scaled case - Calculated values – Design	
Flow rate, kg/s	4400
Power Output, kW	3090
Turbine inlet velocity, m/s	13
Turbine pressure drop, Pa	923
Flow | Work coefficients	0,32 | 0,50
Total-to-static efficiency	0,73

4. Conclusions

The model is a first attempt to a complete simulation of the standard solar chimney system (collector, axial turbine and tower), considering the complete coupled off-design performance of its three fundamental components.

The collector was simulated by a complete heat transfer model (radiation, convection and conduction) considering the fundamental properties and applying well-established correlations for heat transfer and friction.

The design of the turbine confirmed the fundamental guidelines which can be found in the literature, leading to a relatively high degree of reaction and values of the flow and work coefficient compatible with turbine operation within a natural-draft, buoyancy-driven flow.

For off-design performance prediction of the turbine, a simplified global correlation was applied to assess the decrease of turbine efficiency when operating under off-design conditions.

The tower is modeled as a buoyancy-driven flow channel with rough walls and low-conductivity material.

The results consider a reference day in July using meteorological data from Caceres (SP).

In the small-size reference case (a SC similar to the Manzanares unit), the degree of reaction was set at DR = 0,7; Φ = 0,35; Ψ = 0,46; the resulting design value of η_{ts} was 0,67; in the reference day of July, the SC would be able to produce about 650 kWh. As an upscaling design exercise, a large unit with a 1000 m tower was also considered, which led to a nominal 3,1 MWe turbine with a productivity of about 29000 kWh in the same reference day.

The results confirm that the model – which is largely improvable and extendable – is able to provide sensible results and that in a correct evaluation of the system the turbine should be designed to compensate to the possible extent the lower performance of the heat transfer/buoyancy driven flow mechanism, which has a poor performance under conditions of low radiation.

Acknowldgments

The Authors are indebted to Mr. Andrea Orlandi for preliminary student work on the model, and to Dr. Riccardo Secchi for the meteorological data input.

Nomenclature

A	cross section of flow passage, m^2
c_p	constant-pressure specific heat, J/(kg K)
D	diameter, m
DR	degree of reaction
D_h	hydraulic diameter, m
f	friction coefficient
g	gravitational constant, m/s^2
G	radiation of the sun, W/m^2
h	heat transfer coefficient, $W/(m^2\ °C)$
H	height of the tower
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
r	radius, m
s	thickness (glass cover), m
R	friction loss, J/kg
S	surface, m^2
T	temperature, °C
u	peripheral speed, m/s
v	velocity, m/s

W	specific work, J/kg
Q	heat per unit mass flow, J/kg

Greek symbols

α	absorbance
δ	rugosity, m
Δh	enthalpy drop, J/kg
ε	emissivity
η	efficiency
λ	thermal conductivity, W/(m °C)
ρ	reflectance
τ	transmissivity
Φ	Flow coefficient
Ψ	Load coefficient

Subscripts and superscripts

a	air
av	average
ax	axial
c	cover
coll	collector
d	diffuse
dw	down side
e	external
g	ground
i	internal
r	radiative
rot	rotor
st	stage
t	tower
ts	total-to-static
up	upper side
0	section 0 (inlet)
1	section 1 (solar coll. outlet/turbine inlet)
2	section 2 (tower outlet)

References

[1] H.-J.Niemann, F.Lupi, R.Hoeffer, W.Hubert, C. Borri, The Solar Updraft Power Plant: Design and Optimization of the Tower for Wind Effects, Proceedings of EACWE 5, Firenze, Italy, 2009

[2] The Solar Chimney, Schlaich Bergermann und Partners, 2002 (available at http://www.sbp.de)

[3] W. Haaf, K. Friedrich, G. Mayr, J. Schlaich, Principle and Construction of the Pilot Plant in Manzanares, International Journal of Solar Energy, 2,1 (1983), 3-20.

[4] T.P. Fluri, J. P. Pretorius, C. Van Dyk, T.W. Von Backström, D.G. Kröger, G.P.A.G. Van Zijl, Cost analysis of solar chimney power plants, Solar Energy 83 (2009) 246–256

[5] T.W. von Backström, R. Harte, R. Höffer, W.B. Krätzig, D.G. Kröger, H.J. Niemann, G.P.A.G. van Zijl (2008). "State and Recent Advances in Research and Design of Solar Chimney Power Plant Technology", VGB PowerTech 88

[6] T.P. Fluri, T.W. Von Backström, Performance analysis of the power conversion unit of a solar chimney power plant, Solar Energy 82 (2008) 999–1008

[7] T.W. von Backström, T.P. Fluri, Maximum fluid power condition in solar chimney power plants – An analytical approach, Solar Energy 80 (2006) 1417–1423
[8] R. Petela, Thermodynamic study of a simplified model of the solar chimney power plant, Solar Energy 83 (2009) 94–107
[9] J.P. Pretorius, D.G. Kröger, Critical evaluation of solar chimney power plant performance, Solar Energy 80 (2006) 535–544
[10] A. Koonsrisuk, T. Chitsomboon, Partial geometric similarity for solar chimney power plant modeling, Solar Energy 83 (2009) 1611–1618
[11] A. Koonsrisuk, T. Chitsomboon, A single dimensionless variable for solar chimney power plant modeling, Solar Energy 83 (2009) 2136–2143
[12] M. A. dos Santos Bernardes, T.W. Von Backström, G.D. Kröger, Analysis of some available heat transfer coefficients applicable to solar chimney power plant collectors, Solar Energy 83 (2009) 264–275
[13] C.B. Maia, J.O. CastroSilva, L. Cabezas-Gómez, S.M. Hanriot, A.G.Ferreira, Energy and exergy analysis of the airflow inside a solar chimney, Renewable and Sustainable Energy Reviews 27 (2013) 350–361
[14] T.W. von Backström, A.J. Gannon, Solar Chimney Turbine Characteristics, Solar Energy 76 (2004), 235-241
[15] S. Khoshmanesh, M. Mouji, S. Bordbar Solar Turbine, Flow Passage Design, Renewable Energy and Power Quality Journal 12 (2014), http://www.icrepq.com/RE&PQJ.html.
[16] A. Asnaghi, S. M. Ladjevardi, A. Haghparast Kashani, P. Saleh Izadkhast, Solar Chimney Power Plant Performance Analysis in the Central Regions of Iran, Journal of Solar Energy Engineering, ASME 2013, Vol. 135
[17] E.Shams , A.Gross, H.Fasel, Performance Analysis of Solar Chimneys of Different Physical Scales Using CFD, Proceedings of the ASME 2011 5th International Conference on Energy Sustainability ES2011
[18] J.A. Duffie, W. A. Beckman, 1991, *Solar Engineering of Thermal Processes*, 2nd Ed. Wiley Interscience, NewYork.
[19]M.A. dos S. Bernardes, A. Voß, G. Weinrebe, Thermal and technical analyses of solar chimneys, Solar Energy 75 (2003) 511–524
[20] G.F. Nellis, S.A. Klein, Heat Transfer, Cambridge University Press, 2009
[21] http://www.fchart.com/ees/
[22] T.W. von Backström and A.J. Gannon, Solar Chimney Turbine Characteristics, Proceedings of the ISES 2001 Solar World Congress , 935-942
[23] S.L. Dixon, *Fluid Mechanics and Thermodynamics of Turbomachinery*, Elsevier, 2005.
[24] R.J. Latimer, Axial Turbine Performance Prediction, VKI LS Off-design performance of gas turbines, 1978
[25] J. Schlaich, R. Bergermann, W. Schiel, G. Weinrebe, Design of Commercial Solar Updraft Tower Systems – Utilization of Solar Induced Convective Flows for Power Generation, J. of Solar Energy Engineering127 (2005), 117-124