

EFFICIENCY OF SOLAR AIR TURBINE POWER STATIONS WITH FLOATING SOLAR CHIMNEYS

Prof. Christos D. Papageorgiou
 School of Electrical & Computer Engineering N.T.U.A.
 Electrical Machines Laboratory
 Nymfon 1b Kifissia 14563 Athens
 Greece
 chrpapa@central.ntua.gr

Abstract

A solar turbine power station (STPS) has three major components:

- A circular solar collector
- A solar chimney in the center of the solar collector
- A set of air turbo generators near the entrance of the solar chimney

The power output of a STPS is roughly proportional to the height of the solar chimney and the surface area of its solar collector.

In order to increase the power output and the efficiency of a STPS with a given solar collector, we must increase the height of its solar chimney. This can be achieved using floating solar chimneys. The floating solar chimney (FSC) invented by the author, is a lighter than air construction, made by successive balloon rings, that are filled with He or NH₃. This permits to the FSCs to float in the air and thus to have heights up to several Km with any appropriate internal diameter.

In the present paper an extensive presentation of the power output and the efficiency of the STPSs with FSCs is given. As it is shown the power output and the efficiency of the STPS depend on the dimensions of the FSC and the solar collector on the loss coefficients of its FSC and on the environmental characteristics (solar irradiance, temperature and pressure). The efficiency of a STPS with a rated power output of 100 MW is between the ranges of 4.5% to 7% if its FSC heights are in the range of 3000 m to 4500 m.

Key Words

Efficiency, power output, solar air turbine power stations, floating solar chimneys.

1. Introduction

The solar air turbine power stations (STPSs) were invented by prof. J. Schlaigh. In his book ref. [1] Schlaigh gives an extensive presentation fir the STPS. The STPS is mainly a set of three components:

- A large circular solar collector of external diameter D_c
- A tall solar chimney in its center with internal diameter d and height H
- A set of air turbo generators near the bottom of the solar chimney

An indicative diagram for a STPS is shown in fig.1.

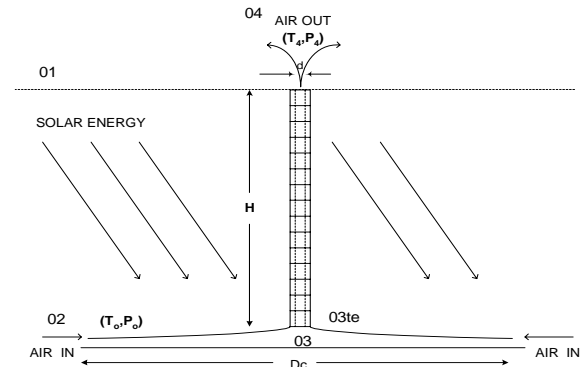


Fig.1

Due to greenhouse effect the air is warmed in the solar collector. The warm air is moving from the periphery of the solar collector to its center towards the entrance of the solar chimney, in order to ‘‘escape’’ to upper layers of troposphere at the output of the solar chimney (see fig.1). This moving stream of warm air leaves part of its thermodynamic energy to the air turbines that are geared with appropriate electric generators. These electric generators are producing finally electric power. The thermodynamic cycle of the STPS is shown in fig.2. The solar chimney has to be constructed by reinforced concrete. Prof. Schlaigh believes that concrete solar chimneys up to 1000 m height, can be constructed. Following his idea EnviroMission Ltd of Australia is now constructs a STPS of 200 MW see www.enviromission.com.au.

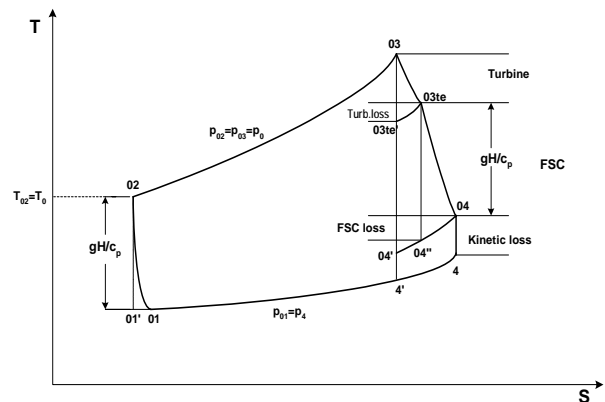


Fig.2

The author with his inventions [2, 3], proposed to make solar chimneys as lighter than air constructions, made by light enduring fabric, used in balloon and airship industry. The author believes that such constructions, that can float in the air and were named floating solar chimneys (FSCs), can encounter effectively the operational sub pressure and the external winds. In paper [4], the author made an initial presentation of the properties and operational characteristics of STPSs with FSCs. The analysis of the paper [4] was based on the thermodynamic cycle analysis presented by Von Barckstrom and Gannon in a series of papers [5,6,7,8].

In paper [9] the author gave an extensive presentation of the performance of the FSCs under external winds. The author papers can be found also in www.floating-solar-chimney.gr

In the present paper an extensive study for the power output and efficiency of STPSs with FSCs is given.

The power output and efficiency of a STPS can be maximized for an appropriate value of the moving air mass (\dot{m} in Kg/sec). It will be shown that this air mass for optimum operation of the STPS is almost independent of the solar irradiance G . For a given solar irradiance this operational power output and the respective efficiency of the STPS depend mainly on the diameter of solar collector (D_c), the height (H) and the internal diameter (d) of its FSC. The effect on the efficiency of the friction loss coefficient of solar chimney (k), and its kinetic energy correction coefficient (α), are presented also. There is also a minor dependence of its efficiency on the environmental conditions in the place of installment of the STPS represented by the environmental temperature T_o and pressure P_o .

As it will be proved the efficiencies of STPSs with FSCs, with heights H in the range of 3000 m to 4500 m, are in the range of 4.5% to 7%, including night operation and stored energy effects.

These efficiencies combined with a rather simple and non-expensive construction for the STPS with FSCs will give economic viability and thus the opportunity to construct and use STPSs for electric power production and to accelerate the procedure towards a future free of harmful to the environment fuels.

I believe that the experience and know-how by constructing STPSs with FSCs will give the opportunity, in the near future, to operate such solar power stations, made by advanced composite materials, that will have construction costs per rated KW in the order of 650 USD, with annual power productions not less than 3000 KWh per rated KW.

2. The efficiency of the solar collector of the STPS.

Although a more elaborating study for the solar collector could be used following for example the method proposed in ref. [5], I believe that the proposed in ref. [1] approximate equation, for the operation of a cyclical solar

collector of the STPS, is almost accurate. Following this the solar collector equation is given by:

$$\left[(\tau_{in, glass} \cdot \alpha_{soil}) \cdot G - b \cdot \Delta T \right] \cdot A_c = \dot{m} \cdot C_p \cdot \Delta T \quad (1)$$

where

$\tau_{in, glass}$ = glass transmittance for solar irradiation

α_{soil} = soil absorptance of solar irradiation

G = solar irradiance

b = equivalent heat losses coefficient of solar collector

$\Delta T = T_o - T_{o3}$

T_o = environmental temperature near the periphery of the solar collector (entry air temperature)

T_{o3} = exit air temperature near the center of the solar collector, just before the air turbines.

A_c = surface area of solar collector

\dot{m} = air mass in Kg of moving air per second

C_p = 1005 Joule/kg °K

For an appropriate choice of material (glass, soil) and dimensions of the cyclical solar collector the following values can be considered as reasonable:

$$\tau_{in, glass} \cdot \alpha_{soil} \approx 0.8$$

$$b \approx 5.5 \text{ W/m}^2 \cdot \text{T}^\circ$$

The efficiency of the solar collector (η_{sc}) is the ratio of solar power given to the air divided by the overall irradiation on the solar collector surface.

$$\eta_{sc} = \frac{\dot{m} \cdot C_p \cdot \Delta T}{G \cdot A_c} = \tau_{in, glass} \cdot \alpha_{soil} - \frac{b \cdot \Delta T}{G} \quad (2)$$

For an average increase temperature $\Delta T = 30^\circ\text{C} - 35^\circ\text{C}$, that is achieved near the operation point for the STPS, and $G_{av} = 800 \text{ W/m}^2$, the solar chimney efficiency is estimated, by the previous formula to be in the range of $\eta_{sc} = 0.6 - 0.56$. Thus the given formula is a reasonable estimation for an appropriately designed cyclical solar collector of the STPS.

3. The efficiency of the air turbines and electric generators of the STPS.

The moving stream of warm air towards the entrance of the solar chimney is carrying a thermodynamic power $\dot{m} \cdot C_p \cdot \Delta T$. Part of this power is detained by the air turbines. This part becomes finally electric output power plus thermal power losses to this electric power production system. The power losses are mainly created in the air turbines. The efficiency of the air turbines depends mainly on the load factor ϕ defined as the ratio of the inlet air speed to the tip speed. A typical curve relating the efficiency and ϕ , for a given pitch angle γ of the blades and flap angle of the inlet guiding vanes, is shown in fig. 3, see ref. [8].

Electric generators, power electronics and gearboxes create also power losses. Usually for an appropriately designed STPS the overall losses of the turbo generators are in the range of 20% near the operation point. Hence for simplicity we keep the efficiency of the turbo generators η_T , as a constant equal to 0.8.

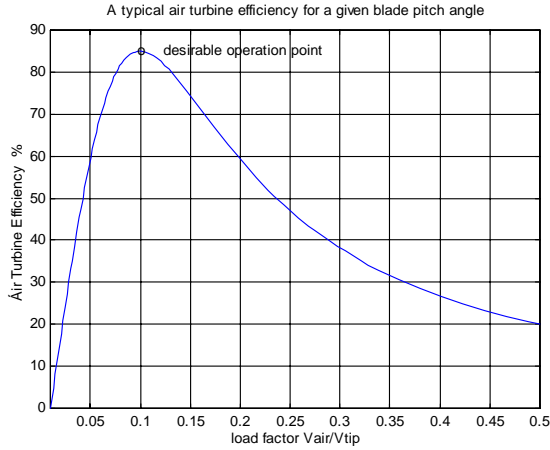


Fig.3

4. The losses in the solar chimney of the STPS.

The warm air, that is moving toward the top of the solar chimney, leaves part of its thermal power to the chimney. The chimney is a tube and the warm air is a fluid moving inside that tube. Usually fluid motion losses in tubes are of two types:

- Losses in specific points where there exist an obstacle or a change in its diameter, or a change in the direction of the fluid velocity.
- Friction losses in the internal surface of the tube.

Both types of losses are approximately proportional to the kinetic energy of the fluid. However this kinetic energy in FSC is not a constant. In fact the air density is decreasing with altitude while \dot{m} remains constant, thus its speed is increasing with altitude for a constant internal diameter. Approximately we can consider the overall losses proportional to the exit kinetic power of the fluid. This exit kinetic power of the warm air equals to:

$$\dot{E} = \alpha \cdot \frac{1}{2} \cdot \dot{m} \cdot U_{exit}^2 \quad (3)$$

Where α is the kinetic energy correction coefficient and U_{exit} is the average air speed in the exit. The coefficient α is related to the profile of air speed in the cyclical cut of the FSC.

This velocity profile in a cut of the FSC can be approximated by an exponential function of radial distance r , see ref. [10].

$$U_{(r)} = U_o \cdot \left(1 - \frac{2 \cdot r}{d}\right)^n \quad (4)$$

For a turbulent flow, n is between 1/5 and 1/9, and hence it can be proved that the exit kinetic energy must be multiplied by the kinetic energy correction coefficient α that is between 1.1058 and 1.037. The mass flow is calculated by the formula $\dot{m} = \rho_{exit} \cdot A_{exit} \cdot U_{exit}$ where $\rho_{exit} \cdot A_{exit}$ are the air density and solar chimney cut surface in the exit.

Thus if $P_{L,ch}$ is the solar chimney losses we consider that

$$P_{L,ch} = k \cdot \dot{E} \quad (5)$$

where k is a constant, independent of U_{exit} .

For a constant internal diameter of the solar chimney in any altitude, we can consider that k is composed by two parts, a constant part related with the entrance of warm air from the solar collector to the solar chimney, and a variable part that is proportional to the height of the

$$\text{chimney } H, \text{ thus: } k = k_o + k_1 \cdot \frac{H}{H_o} \quad (6)$$

The kinetic power of the warm air, in the exit of the FSC, is unused warm air power that is dissipated in the upper layers of the troposphere. Hence the overall losses in the solar chimney are $(k + 1) \cdot \dot{E}$ (7)

The dynamic mechanical power, of the climbing on the top of the solar chimney warm air, is not losses, because this air goes down to the ground, increasing its temperature to the environmental temperature T_o , thus it is added back to the system. This it is evident in the thermodynamic cycle diagram of fig. 2.

5. The efficiency of the STPS.

It has been proved in ref. [4] that using a fourth order polynomial equation we have finally the relation:

$$P_T = C_p \cdot \dot{m} \cdot C_p \cdot (T_{o3} - T_{o3,te}) \quad (8)$$

Where P_T is the electric power output of the STPS and \dot{m} is the moving air mass in Kg/sec, $C_p = 1005$ Joule/kg °K, T_{o3} , $T_{o3,te}$ are the entry and exit air temperatures in the air turbo generators given through a set of equations as functions of \dot{m} and the parameters d , H , D_c , G , k , α , T_o , P_o , η_T (see Appendix I).

The efficiency of the STPS is given by the formula

$$\eta = \frac{P_T}{A_c \cdot G} \quad (9) \text{ where } A_c \cdot G \text{ is the solar irradiation}$$

power arriving on the horizontal solar collector surface area A_c . This efficiency is the efficiency for a given value of solar irradiance G .

As an example let us consider a STPS having the following dimensions and constants:

$D_c = 1770$ m, $d = 70$ m, $H = 3500$ m, $k = 1.667$, $\alpha = 1.1058$, $\eta_T = 0.8$. The average environmental temperature is $T_o = 303.2$ °K and the pressure is $P_o = 101000$ Pa. The solar irradiance G is varying between 200 W/m² to 1000 W/m². In figure 4 the effect of the G on the power output of this STPS is shown.

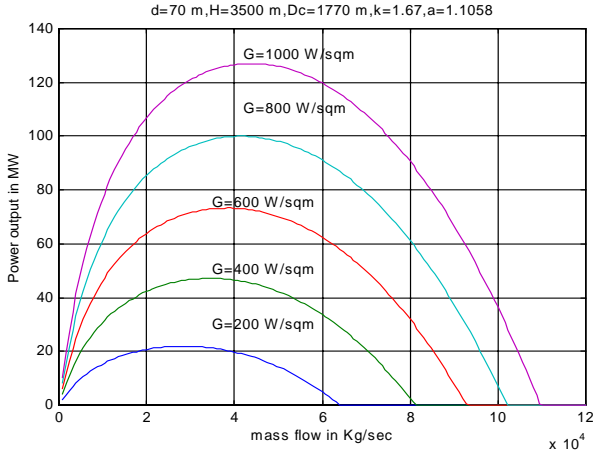


Fig.4

If the average G is 800 W/m^2 the maximum power output for this STPS, that is achieved for $\dot{m}_M = 41460 \text{ Kg/sec}$ is 100 MW . Let us assume that the rated power output P_R of a STPS is the maximum power output for the average solar irradiance. This means that the STPS under consideration will have a rated power of 100 MW . As we can observe by fig. 4, the maximum power output point of operation (\dot{m}_M) is approximately constant for any solar irradiance G , near G_{av} .

Let us arrange the annual daylight solar irradiance in the place of installment of the STPS G in a descending order of magnitude, as a function of its time duration Δt . We can assume that approximately this function is given by the formula

$$G_{(t)} = G_{\max} - (G_{\max} - G_{\min}) \cdot \left(\frac{t}{t_o}\right)^r \quad (10)$$

Where G_{\max} , G_{\min} is the maximum and minimum used daylight solar irradiance in day light operation process of the STPS, and t_o is the annual duration (in hours) of the daylight operation.

It can be easily proved that $r = \frac{G_{av} - G_{\min}}{G_{\max} - G_{av}}$ (11)

where G_{av} is the average solar irradiance.

For example for $G_{\max} = 1000$, $G_{\min} = 100$, $G_{av} = 800$, $r = 3.5$. Thus for this specific place of installment of the STPS:

$$G_{(t)} = 1000 - 900 \cdot \left(\frac{t}{t_o}\right)^{3.5} \quad (12)$$

Let us calculate, for the previously defined STPS the average annual power output P for constant \dot{m}_M where \dot{m}_M is the value of mass airflow for which the STPS power is maximized for the average irradiance G_{av} .

This average power output is given by

$$\frac{1}{t_o} \cdot \int_0^{t_o} P_T(\dot{m}, G(t)) dt \quad (13)$$

That can be approximated by the sum

$$P = \frac{1}{N} \cdot \sum_{n=1}^N P_T\left(\dot{m}, G = 1000 - 900 \cdot \left(\frac{n-0.5}{N}\right)^{3.5}\right) \quad (14)$$

The calculated value of P is only 0.023% smaller than $P_{\max}(G_{av})$. Practically similar results are achieved for any reasonable choices for G_{\max} , G_{\min} and G_{av} .

Similar calculations with \dot{m} varying linearly around \dot{m}_M gave similar results.

This means that to operate a STPS near the point of maximum power output \dot{m}_M is a very good choice. If we operate the STPS in this way we can consider that practically the maximum power output for the daily and annual operation is achieved by the STPS. The average irradiance G_{av} can be calculated as the ratio of the annual energy in KWh per sqm of horizontal surface divided by the insolation hours of the year. Following this operation procedure for the STPS its average annual efficiency is

$$\text{approximately equal to } \eta = \frac{P_{\max}(G_{av})}{G_{av} \cdot A_c} \quad (15)$$

hence the efficiency and maximum power output for average irradiance are proportional.

However in order to take into consideration the night operation (and the effects during the day by the stored thermal energy in the soil of the solar collector) we should increase the annual efficiency by $(5\% \text{ to } 10\%)$, hence a reasonable estimation for the overall annual efficiency of a STPS could be

$$\eta_o = 1.07 \cdot \left[\frac{P_{\max}(G_{av})}{G_{av} \cdot A_c} \right] \quad (16)$$

6. Dimension variation of the STPS.

Let us now examine the effect of basic dimensions variation on the efficiency of the STPS. As an example we use the STPS of 100 MW with dimensions $d=70 \text{ m}$, $H=3500 \text{ m}$, $D_c=1770 \text{ m}$, and constants as previously defined.

The figures (5, 6, 7) show the effect, on the overall efficiency η_o of the dimensions variation as follows:

- Internal FSC diameter $50 \text{ m} \leq d \leq 100 \text{ m}$
- Solar collector diameter $1500 \text{ m} \leq D_c \leq 2000 \text{ m}$
- Height of the FSC $2500 \text{ m} \leq H \leq 4500 \text{ m}$

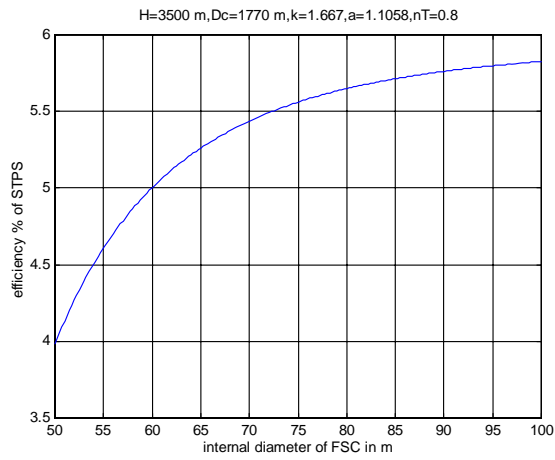


Fig.5

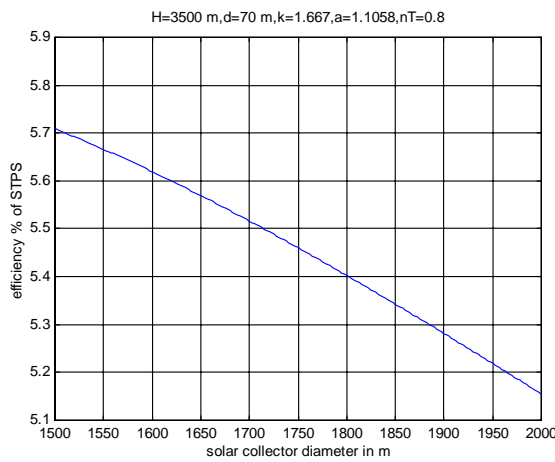


Fig.6

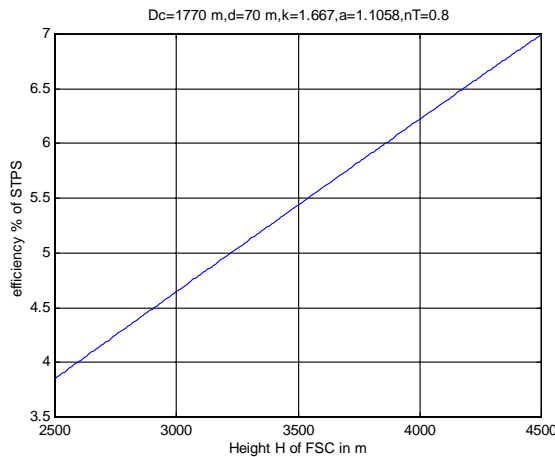


Fig.7

We assume that k depends on H by the relation

$$k = 0.5 + \frac{H}{3000}$$

7. Sensitivity analysis for coefficients k , α , of the FSC and environmental parameters T_o , P_o .

Let us now examine the effects on the efficiency of the variation of friction coefficients k and kinetic energy correction coefficient α . In the figures 8 and 9 are presented the effects by the variation of these parameters. For $d=70$ m, $H=3500$ m, $D_c=1770$ m, $\eta_1=0.8$, $T_o=303.2^\circ\text{K}$, $P_o=101000$ Pa and $0.7 \leq k \leq 2.2$, $1.05 \leq \alpha \leq 1.2$.

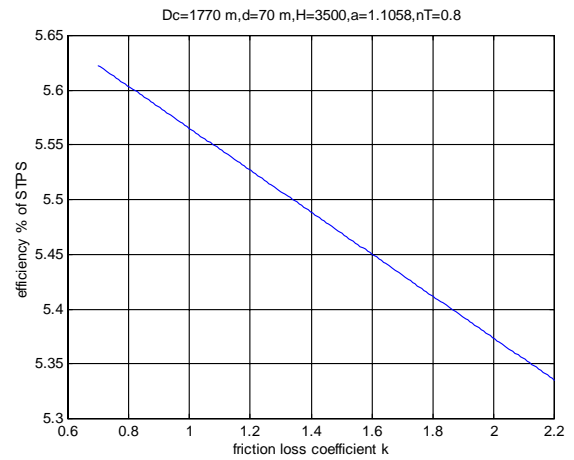


Fig.8

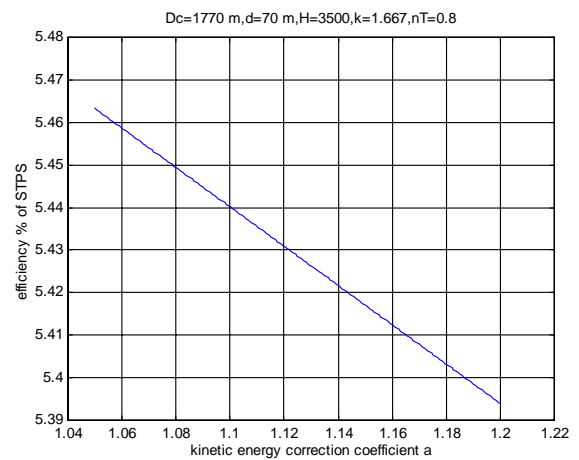


Fig.9

The effects of the environmental parameters variation on the efficiency of the STPS is shown in figures 10 and 11 for $293^\circ\text{K} \leq T_o \leq 313.2^\circ\text{K}$, $95000 \text{ Pa} \leq P_o \leq 105000 \text{ Pa}$

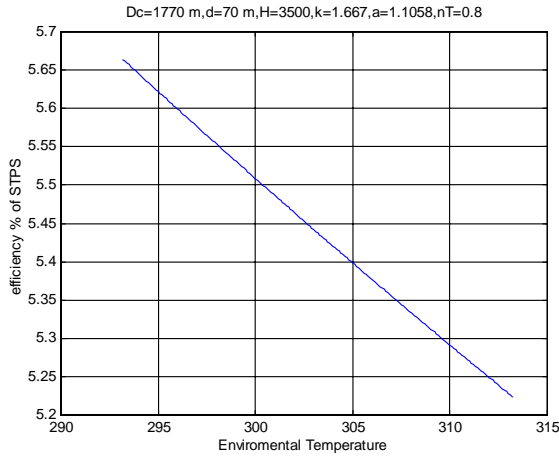


Fig.10

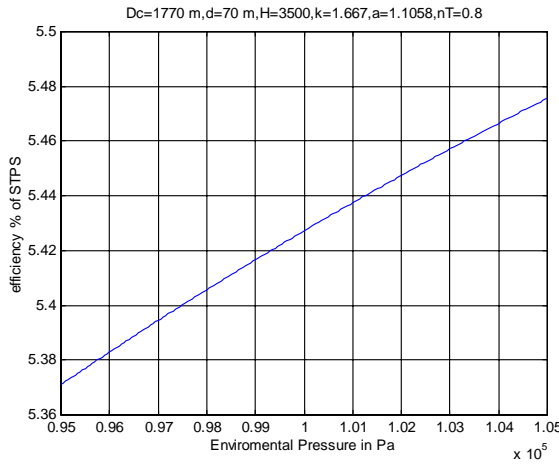


Fig.11

8. Annual energy production

The annual energy production of STPS is calculated by the formula

$$\eta_o \cdot P_y \cdot A_c = \eta_o \cdot G_{av} \cdot A_c \cdot N = 1.07 \cdot P_r \cdot N \text{ in KWh} \quad (17)$$

Where P_y is the annual solar energy in a horizontal surface in KWh/m², P_r is the rated power output of the STPS calculated by the relation $P_r = P_{\max}(G_{av})$, N is the daylight hours per year, 1.07 is the correction coefficient due to stored energy and night operation of the STPS. Usually 1.07·N is bigger than 3000, for an appropriate place of installment of the STPS. Hence the annual energy production, per KW of rated power output, is more than 3000 KWh.

9. Conclusions

In the present paper the efficiency of solar power stations with air turbines (STPSs) and floating solar chimneys (FSCs) was examined. It was shown that the STPS operating near the point of maximum power output for the average solar irradiance G_{av} , has its maximum efficiency

and this, including night operation, is approximately

given by the relation $\eta_o = \frac{1.07 \cdot P_r}{G_{av} \cdot A_c}$ (18) where :

- P_r is the rated power output of the STPS calculated as its maximum power output for G_{av} .
- A_c is the surface area of the solar collector

The annual energy production is $\eta_o \cdot P_y \cdot A_c$ where P_y is the annual irradiation energy arriving on a horizontal surface per sqm.

The sensitivity of the efficiency of the STPS was examined under the variation of its main dimensions (d , H , D_c), the operating coefficients of the FSC (k , a) and the air conditions near the entrance of the solar collector (T_o , P_o).

The efficiency of the turbo generators was considered constant and equal to 0.8.

The efficiencies of the STPS for appropriate FSC with height between 3000 m to 4500 m was calculated and in average is between 4.5% and 7%. The STPS, installed in appropriate places, produce per year more than 3000 KWh per rated KW.

Appendix I

In the Appendix the equations for a STPS are given as was presented in ref. [4]. A STPS has a thermodynamic cycle shown in fig. (2).

A. Symbol explanations

- α – kinetic energy correction coefficient
- A_c – solar collector surface area $\approx \pi D_c^2/4$ in m²
- C_p – isobaric specific heat = 1005 Joule/Kg·°K
- d – internal FSC diameter in m
- D_c – solar collector diameter in m
- g – gravity constant = 9.81 m/sec²
- G – solar irradiance in W/m²
- H – FSC height in m
- k – FSC friction loss coefficient
- \dot{m} – mass air flow in Kg/sec
- η_T – turbo generators efficiency
- $p_0 = p_{02} = p_{03}$ –stagnation air pressure in the solar collector
- p_0 – environmental pressure in the entrance of solar collector
- p_4 – static air pressure in the exit of the FSC
- P_T – electric power output in W by turbo generators
- R – air constant = 287 Joule/Kg·°K
- $T_{02} = T_0$ – environmental temperature in the entrance of solar collector
- T_{03} – Temperature at the exit of solar collector that is the entry temperature of the air in the air turbines
- T_{03te} – warm air exit stagnation temperature from the air turbines

T'_{03te} - isentropic exit stagnation temperature from the air turbines

T_{04} - stagnation air temperature in the exit of the FSC

T_4 - static air temperature in the exit of the FSC

T'_4 - isentropic static air temperature in the exit of the FSC

T_{01} - stagnation temperature in the output altitude of the FSC

T'_{01} - stagnation isentropic temperature in the output altitude of the FSC

v_{exit} - air speed in the exit of FSC

z - altitude in m

B. The Equations

$$T_{o3} = \left[\frac{\tau_{in} a_s G}{\beta + \dot{m} C_p / A_c} \right] + T_o \text{ by the solar collector}$$

thermal equation

$$T'_4 = T_{o3} \left(1 - \frac{gH}{C_p T_o} \right) \text{ by the thermodynamic cycle (fig.2) for isentropic processes between isobaries}$$

$$p_4 = p_o \left[1 - \left(\frac{gH}{C_p T_o} \right) \right]^{3.5}$$

$$w_1 T_4^4 + w_2 T_4^3 + w_3 T_4^2 + w_4 T_4 + w_5 = 0$$

where w_1, w_2, w_3, w_4, w_5 are given by the relations

$$w_1 = C_2^2 (1 - k)$$

$$w_2 = C_2 (2 - k - n_T C_2 T'_4)$$

$$w_3 = C_2 C_3 (1 - k) + 1 - 2n_T C_2 T'_4$$

$$w_4 = C_3 - n_T T'_4 (1 + C_1 C_2)$$

$$w_5 = -n_T T'_4 C_1$$

where

$$C_1 = \frac{gH}{C_p}$$

$$C_2 = \frac{a}{2C_p} \left(\frac{R\dot{m}}{\left(\pi \frac{d^2}{4} \right) p_4} \right)^2$$

$$C_3 = T_{o3} (n_T - 1) + C_1$$

T_4 is the real root of the fourth order polynomial equation near to T'_4

$$P_T = C_p \cdot \dot{m} C_p (T_{o3} - T_{o3te})$$

$$\text{where } T_{o3te} = T_4 + C_1 + C_2 T_4^2$$

$$n = n_{FSC} n_C = \frac{P_T}{A_c G} \text{ STPS efficiency}$$

$$\Delta p = p_{exit} - p_o = p_o \left[1 - \frac{P_T}{\dot{m} C_p n_T T_{o3}} \right]^{3.5} - p_o$$

maximum sub pressure in the bottom of the chimney

$$\Delta p(z) = p_{in(z)} - p_{out(z)} \text{ maximum sub pressure at altitude } z \text{ approximately given}$$

Where

$$p_{in(z)} = p_{exit} \left(1 - \left(1 - \frac{T''_{o4}}{T_{o3te}} \right) \frac{z}{H} \right)^{3.5}$$

$$p_{out(z)} = p_o \left(1 - \frac{\Delta T}{\Delta z} \frac{z}{288.16} \right)^{5.26} \text{ (White [10])}$$

$$v_{exit} = \frac{\dot{m}}{\rho A} = \frac{\dot{m} R T_4}{A p_4}$$

References:

- [1] Schlaigh J. 1995, "The Solar Chimney : Electricity from the sun" Axel Mengers Edition.
- [2] Papageorgiou C. 2003, "Floating Solar Chimney" PCT/GR03/00037/27-03-2003
- [3] Papageorgiou C. 2004 "Wall Construction for Floating Solar Chimneys" Patent G.R. 20040100092/16-03-2004
- [4] Papageorgiou C. 2004 "Solar Turbine Power Stations with Floating Solar Chimneys". IASTED Proceedings of Power and Energy Systems, EuroPES 2004. pp.151-158
- [5] Gannon A. , Von Backstrom T 2000, "Solar Chimney Cycle Analysis with System loss and solar Collector Performance", Journal of Solar Energy Engineering, August Vol 122/pp.133-137.
- [6] Von Backstrom T, Cannon A. 2000, "Compressible Flow Through Solar Power Plant Chimneys". August vol 122/ pp.138-145.
- [7] Von Backstrom T. 2003, "Calculation of Pressure and density in Solar Power Plant Chimneys", Journal of Solar Energy Engineering, February 2003, Vol125 pp.127-129
- [8] Gannon A. , Von Backstrom T 2003, "Solar Chimney Turbine Performance", Journal of Solar Energy Engineering, February Vol 125/pp.101-106.
- [9] Papageorgiou C. 2004, "External Wind Effects on Floating Solar Chimney". IASTED Proceedings of Power and Energy Systems, EuroPES 2004 pp.159-163
- [10] White F. 1999, "Fluid Mechanics" 5th Edition McGraw-Hill N, York.