Floating Solar Chimney versus Concrete Solar Chimney Power Plants

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***Abstract*--A solar chimney power plant has three major components:**

- **A circular solar collector (Greenhouse)**
- **A tall cylinder in the center of the solar collector (Solar Chimney)**
- **A set of air turbines geared to electric generators around the bottom of the solar chimney**

The air warms up inside the greenhouse by the solar irradiation and, due to its buoyancy, tends to escape through the Solar Chimney. This warm stream of air is leaving part of its thermodynamic energy to the air turbines placed in the path of the airflow. The solar chimney power stations were named Solar Aero-Electric Power Plants (SAEPPs) due to their similarity to Hydro Electric Power Plants. The efficiency of the SAEPPs is roughly proportional to the height of their solar chimneys.

Solar Chimneys can be made as reinforced concrete structures (Concrete Solar Chimneys, CFCs), or as lighter than air inflated structures (Floating Solar Chimneys FSCs). These floating solar chimneys are made by successive balloon tubes, filled with a lighter than air gas. This permits to the FSCs to float in the air and thus to have heights 1.5÷3 Km giving to their SAEPPs higher efficiencies than Concrete Solar Chimney SAEPPs.

Using ground thermal storage, or artificial thermal storage in the form of water in closed plastic tubes, it can be proved that the SAEPPs can operate 24 hours per day 365 days per year with a minimum guaranteed power production. This means that the SAEPPs, although renewable by nature, can have a similar operation to conventional power stations and thus can replace them.

In the present paper a comparison for construction cost of SAEPPs with Floating Solar Chimneys and Concrete Solar Chimneys is given. It is shown that FSC Technology Power Plants is 5 to 6 times cheaper than CFC Technology Power Plants.

***Index Terms*--Floating Solar Chimney Solar Aero Electric Power Plant**

I. Introduction

A major problem in nowadays is the international tension due to the entrance to the era of the end of oil (and the end of natural gas also). Strong economies and states fill the uncertainty for their power supplies, while the weaker just watch the uprising fuel gas and electricity prices. In the same time the global warming effect is a real threat and the nuclear alternative could be proved a even worst nightmare. The renewable technology either is limited (Hydroelectric), more expensive than conventional Power Plants and with non guaranteed power output production (Wind, Solar PVs, Solar concentrators etc).

In the present paper a new promising technology in solar energy field, the Solar Chimney Technology, is evaluated and its two versions for the construction of the solar chimneys are compared. In fact the solar chimney can be a reinforced concrete structure or an inflated lighter than air structure named Floating Solar Chimney (FSC).

Floating Solar Chimney Power Plants, as will be shown, can have an initial construction cost 5 to 6 times smaller than Concrete Solar Chimney Power Plants, are cheaper than the respective wind farms and for this reason can be the answer to the energy and environment problems supplying the worlds economy with unlimited quantities of Electrical Energy of a guaranteed daily profile Power Output with a very competitive production cost .

Solar Chimney Technology is an electricity power generating method using the thermodynamic cycle of the warm air heated by the solar irradiation in a large solar collector and up drafting through a tall chimney. The moving stream of warm air is leaving part of its thermodynamic energy to a set of air turbines geared to appropriate electric generators that are placed on its path . The Solar Chimney Power Plants were named Solar Aero-Electric Power Plants (SAEPPs) due to their similarity to Hydro-Electric Power plants.

Thus a Solar Aero-Electric Power Plant is a set of three major components:

A circular Solar Collector of diameter D_c with a transparent roof supported a few meters above the ground open in its periphery (The Greenhouse).

A very tall, warm air up drafting cylinder, of height H and internal diameter d, in the center of the Solar Collector (The Solar Chimney).

A set of horizontal axis air turbines geared to appropriate electric generators around the Solar Chimney (The Turbo Generators).

An indicative figure for a SAEPP is shown in fig. (1).

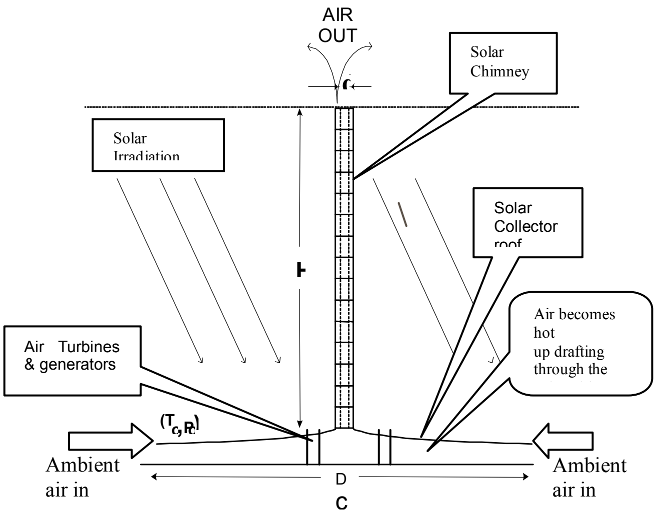

Fig 1. A schematic diagram of a solar chimney power plant

Due to greenhouse effect the air is warmed inside the Solar Collector. The warm air is moving from the periphery of the Solar Collector towards its center to the entrance of the Solar Chimney, in order to ''escape'' to upper layers of atmosphere due to its buoyancy. This moving stream of warm air leaves part of its thermodynamic energy to the air turbines that are geared to appropriate induction electric generators producing finally electric energy. The shrouded axial air turbines are placed in the path of airflow, with their horizontal axis symmetrically around the bottom of the solar chimney.

One of the earliest descriptions of a solar chimney power station was written in 1931 by a German author, Hanns Gunther. More recently Schaich, Bergerman and Partners, under the direction of Prof. Dr. Ing. Jorg Schlaigh, built an operating model of a solar chimney power plant, in 1982 in Manzanares (Spain), 150 km south of Madrid, which was funded by the German Government. This power plant of 50 KW operated successfully for approximately 8 years. The Solar Chimney had a diameter of 10 m and a height of 195 m. Prof. J. Schlaigh in 1996 published a book [1] in order to present this technology.

The collected operational data for by this model agreed perfectly with the results by the theoretical analysis proposed by Prof. J. Schlaigh. A thermodynamic theoretical approach for the operation of Solar Chimney power plants was presented later by Von Backstrom and Cannon [2], [3].

Prof . Jorg Schlaigh proposed, in his book [1], huge reinforced concrete Solar Chimneys. These Solar Chimneys are very expensive constructions and have a height limit (of existing very tall structures) up to 600÷700m, due to concrete and steel specific weights and strength. Even for these heights the efficiencies of the respective SAEPPs are limited, thus their solar collectors should be very large and expensive.

In order to increase the efficiency of Solar Chimney power plants and to decrease their cost, higher Solar Chimneys as lighter than air inflated fabric structures, named Floating Solar Chimneys (FSCs), were invented and studied by the author see ref. [4], [5],[6],[7].

A major advantage of SAEPPs in comparison to other renewable power generation methods (Wind, Solar concentrators, Solar PVs) is their ability, due to ground thermal storage , to produce a guaranteed profile of power for 24h/day, 365days/year see papers ref. [8], [9], [10] and [11].

II. SAEPPS'OPERATIONAL CHARACTERISTICS

An important characteristic curve for a FSCPS operation is the relation $P(\dot{m})$, where P is the electric power output to the grid (in W) and $\dot{m}$ is the moving air mass flow (in Kg/sec) under given ambient temperature T_0 and pressure p_o and solar irradiance on horizontal surface G. The analysis made by the author in [4] can be used for the calculation of the characteristic curve $P(\dot{m})$ of SAEPPs.

A short presentation for the $P(\dot{m})$ algorithm procedure is appearing in Appendix I. The curve $P(\dot{m})$ it depends on the dimensions and fluid or thermal characteristics of the Solar Collector and the up drafting Solar Chimney. It also depends on the combined efficiency n_T (of the air Turbines and electric generators). Various control methods can be used in order the maximum power output to be taken according to the varying external conditions. It can been shown that due to the ground thermal storage the SAEPP can operate 24 hours per day. In figure (2) the variation of Power output P during an average day is shown for a SAEPP with the following FSC's dimensions H=2000m ,d=50m, solar collector with double cover transparent roof of diameter Dc=1643m, installed in a place with annual solar irradiation on horizontal surface 2160000 KWh/m^2, operating on an average power of 13.2 MW and producing annually 116 GWh (approximately this SAEPP has a rating power of 3times its average power i.e.~ 40 MW that is equal to its maximum power production in the hot days of summer).

The same SAEPP but with a single cover solar collector should have an a average power of 10 MW producing annually 85 GWh , thus the double cover solar collector SAEPPs they have a marginally higher initial construction cost but they can produce as much as 40% more electric energy annually.

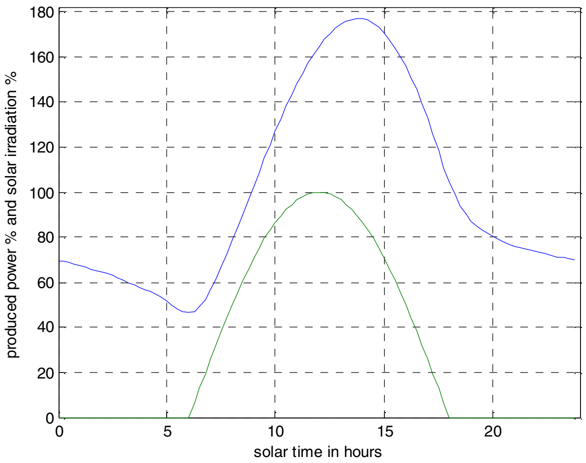

Fig 2. Daily variation of Electric Power(%) and solar irradiance(%) on horizontal surface

A very important result of thermal storage analysis is that the average power of the SAEPP in the 24 hours/day operation is almost independent of its thermal storage and almost equal to the maximum power P_{max} for the average solar irradiance on horizontal surface. This will be achieved under the appropriate regulation of the power production units(Air Turbines and Electric Generators). The P_{max} can be evaluated using the simplified analysis of appendix I. Hence the initial dimensioning of the SAEPPs of given rating power can be estimated using this simplified analysis.

The efficiency of the SAEPP, that is a solar electromechanical system, is defined as the ratio $\eta=P/(A_c \cdot G)$ i.e. the Power output P divided by the solar irradiation power arriving on the solar collector's area.

As P_M is almost proportional to G (actually the ratio P_M/G is slightly decreasing with lower values of G) the overall annual efficiency is approximately given by:

$\eta_y \cong P_M(G_{av})/(A_c \cdot G_{av})$ (1)

where G_{av} is the average operational G defined as the ratio w_y/h_y, where w_y is the annual irradiation arriving on the horizontal surface per m^2 and h_y is the hours of operation of the SAEPP. As h_y is increasing due to thermal storage the G_{av} becomes smaller and thus the efficiency is decreasing slightly. This is a minor negative penalty for the continuous 24 h/day operation of the SAEPP. However for single cover collector SAEPPs the decrease due to its 24 hours operation is substantial thus the double cover collectors should be considered as the proper choice for the SAEPPs.

Thus it is obvious that a well designed SAEPP, regulated to operate on the points of maximum P and operating 24 hours per day due to ground thermal storage (i.e. h_y=8760 hours) will produce annually electric energy given by:

$W_{el}= \eta_y \cdot w_y \cdot Ac \cong h_y \cdot P(G_{av})$ in KWh/year (2)

As rating Power (P_R) of a SAEPP, usually it is defined its maximum Electric Power Output that is the Power output for the hottest days in summer, this maximum is approximately ~3 times bigger than the annual average for ground thermal storage only thus:

$W_y = 8760 \cdot P(G_{av}) = 8760 \cdot P_R/3 \approx 3000 \cdot P_R$ in KWh/year (3)

For SAEPPs without artificial thermal storage. If the SAEPPs have artificial thermal storage plus the natural ground thermal storage the maximum power in hot days of summer that is defined as its rating power, i.e. the overall rating power of their electric generators for example could be 2 times the average power P_{av} thus $Wy \approx 4380 \cdot P_R$ in KWh/year (3a).

As has been proved [6] an inherent characteristic of the SAEPPs is that their efficiency is proportional to the up drafting solar chimney's height H. This property was expected because the SAEPPs are similar to hydro – Electric Power Stations. In fact the hydro - Electric water turbines are operating due to the dynamic energy of the falling water i.e. due to gravity. The SAEPPs' air turbines are working due to the dynamic energy of the up drafting warm air i.e. due to buoyancy. This is reason that I named them Solar Aero electric Power Plants. Hence for more efficient and cost effective SAEPPs very high Solar Chimneys are necessary. The Floating Solar Chimneys can become very tall and their height limit it is depended on techno economic decisions. Thus the Floating Solar Chimneys are excellent inexpensive alternatives to concrete Solar Chimneys giving to their respective SAEPPs higher efficiencies and much lower construction costs.

III. Floating vs Concrete sorar chimneys for a 40 MW SAEPP

Typical curves $P(\dot{m})$ for SAEPPs with a Floating Solar Chimney with heights H=3000m and H=2000m, internal diameter d=50m, and double cover solar collectors with diameters Dc=1280m(Ac=1.23 Km^2) and Dc=1643m(Ac=2.12 Km^2), installed in an area with annual solar irradiation on horizontal surface 2160 KW/m^2 and Turbo Generator's efficiency n_T=0.8, were produced using the algorithm of Appendix I and are shown in fig(3) for an operating estimated maximum irradiance on horizontal surface G=700 W/m^2 and n_T=0.8. As it is obvious the maximum electrical Power output of this Power Plants (rating power) is ~ 40 MW and this is achieved for $\dot{m}$ = 20750 Kg/sec and $\dot{m}$ = 24650 Kg/sec respectively. Various control methods through their Turbo Generators could secure this optimum operation of the SAEPPs for any solar irradiance during its daily and annual operation.

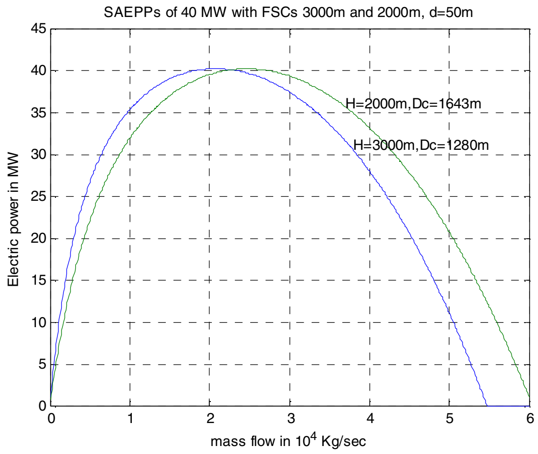

Fig. 3 Maximum Electric power output of two floating solar chimney Power Plants with heights 2000m and 3000m, as functions of mass flow.

The same curves P($\dot{m}$) of two SAEPPs of the same rating power of 40 MW with smaller heights concrete solar chimneys H=500m and H=600m, bigger respective internal diameters d=80m and d=90m, with appropriate solar collectors with diameters Dc=3950m (Ac=12.2Km^2) and Dc=3210m (Ac=8.0Km^2), installed in the same area where the average solar irradiance on horizontal surface is G=700 W/m^2 and n_T=0.8 are shown in fig(4). The maximum electrical Power is achieved for $\dot{m}$ = 62600 Kg/sec and $\dot{m}$ = 66200 Kg/sec, that is why this SAEPP chimney's internal diameter should be bigger 80m and 90m (than the previous of 50m). The Concrete Solar Chimney internal diameters should also be appropriate to its height for foundation reasons.

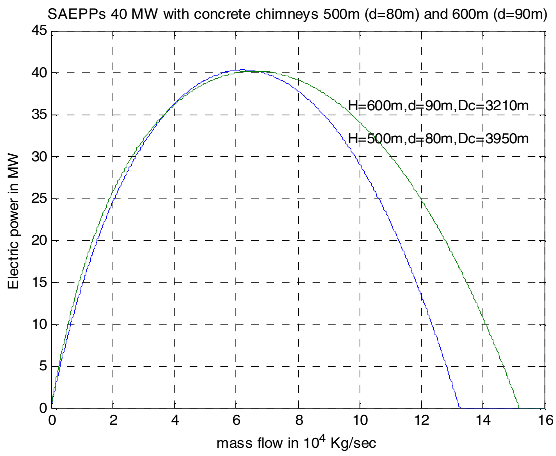

Fig. 4 Maximum Electric power output of two concrete solar chimney Power Plants with heights 500m and 600m, as functions of mass flow.

Assuming that all the 40 MW SAEPPs are equipped with 40 pieces of Air Turbines connected with appropriate gear boxes to their respective Induction Generators of 1 MW the air Turbines' diameter for the three SAEPPs should be ~7.2 m,7.2 m and 12.0 m respectively while their maximum inner solar collector height should be 8 m,8 m and 14 m respectively. Their respective solar collectors will have areas A_c 1230000 m^2, 2120000 m^2, 8000000 m^2 and 12200000 m^2.

The construction cost of the Floating Solar Chimney SAEPP with H=3000m can be estimated by the following approximate analysis:

- Floating Solar Chimney construction cost (100÷120)·d·H=15.0÷18.0 million EUR
- Solar collector Glassed roof construction cost (8÷9)·A_c=10.0÷11.0 million EUR
- Gear boxes, Air Turbines cost (80÷100)·Rating Power in KW=3.2÷ 4.0 million EUR
- Electric Generators Transformers and cabling (100÷150)·Rating Power in KW=4.0÷6.0 million EUR
- **Overall construction cost without land or overhead costs 32.2÷39.0 million EUR**

Following the same analysis the construction cost of the Floating Solar Chimney SAEPP wit H=2000m can be estimated, taking into consideration that D_c=1643m and A_c=2120000 m^2 as follows:

- Floating Solar Chimney construction cost (100÷120)·d·H=10.0÷12.0 million EUR
- Solar collector Glassed roof construction cost (8÷9)·A_c=17.0÷19.0 million EUR
- Gear boxes, Air Turbines cost (80÷100)·Rating Power in KW=3.2÷ 4.0 million EUR
- Electric Generators, Transformers and cabling (100÷150)·Rating Power in KW=4.0÷6.0 million EUR
- **Overall construction cost without land or overhead costs 34.2÷41.0 million EUR**

As it is obvious lowering the FSC to 2000m the overall construction cost for a 40 MW SAEPP is increasing marginally (+5%).

The approximate construction cost of the Concrete Solar Chimney SAEPP of H=500m and d=80m, can be estimated by the following analysis for Ac=12200000 m^2:

- Concrete Solar Chimney construction cost (400÷500)·π·d·H=50.2÷62.8 million EUR
- Solar collector Glassed roof construction cost (9÷10)·A_c=110.8÷122.0 million EUR
- (The bigger cost per m^2 is because the average supporting height of the roof is bigger)
- Air Turbines cost (200÷300)·Rating Power in KW=8.0÷ 12.0 million EUR
- (The bigger cost for the Air Turbines and gear boxes is because Air Turbines they have bigger diameters and gear boxes bigger transmission ratio)
- Electric Gererators , Transformers and cabling (100÷150)·Rating Power in KW=4.0÷6.0 million EUR
- **Overall construction cost without land or overhead costs 173.0÷202.8 million EUR**

The approximate construction cost of the Concrete Solar Chimney SAEPP of H=600m and d=90m, can be estimated accordingly by the following analysis for

A_c=8000000 m^2:

- Concrete Solar Chimney construction cost (500÷600)·π·d·H=84.8÷102.0 million EUR
- (The bigger cost per m^2 is because the height of the chimney is bigger)
- Solar collector Glassed roof construction cost (9÷10)·A_c=72.0÷80.0 million EUR
- Gear boxes, Air Turbines cost (200÷300)·Rating Power in KW=8.0÷ 12.0 million EUR
- Electric Gererators , Transformers and cabling (100÷150)·Rating Power in KW=4.0÷6.0 million EUR
- **Overall construction cost without land or overhead costs 168.8÷200.0 million EUR**

By the comparison of the costs it is evident that the Floating Solar Chimney Power Plants of 40 MW could be 5÷6 times cheaper than the respective Concrete Solar Chimney Power Plants of the same Electric Power Output of 40 MW and they are using areas for their solar collectors 4 ÷ 10 times smaller

A short comparison, at a first approximation, of the Solar Chimney SAEPPs with the most cost effective renewable technology, the Wind Turbines is useful also to be presented.

The construction cost of a wind farm of the same rating Power of 40 MW it is approximately estimated to 40 million EUR, with an average capacity factor of 28%.

The respective Floating Solar Chimney Power Plant of 40 MW should have an average cost of 36 million EUR (-10% of the cost of the respective wind farm) and a capacity factor 33.5% (+20% of the capacity factor of the respective wind farm).

The respective Concrete Solar Chimney Power Plant of 40 MW should have an average cost of 200 million EUR (+400 % of the cost of the respective wind farm) and a capacity factor 33.5% (+20% of the capacity factor of the respective wind farm).

IV. Conclusion

A comparison of the construction cost of Floating Solar Chimney SAEPPs to Concrete Solar Chimney SAEPPs, both with double cover solar collectors and ground thermal storage only, has given for 40 MW Power Plants, indicating that the Floating option could be 5 ÷ 6 times cheaper than its respective Concrete version. The necessary area for the solar collector of the Floating Solar Chimney SAEPP is also 4 ÷ 10 times smaller compared to the area of the solar collector of its respective Concrete Solar Chimney SAEPP.

The high demanded land area and the higher construction cost of the Concrete Solar Chimney Technology per KW in comparison to Wind Turbine Technology cost per KW, to my mind, had made the Concrete Solar Chimney SAEPPs not an attractive option up till now, to the renewable investors.

On the contrary Floating Solar Chimney SAEPPs, demanding far less land, having lower construction cost and bigger capacity factor than their respective wind farms, could be a profit promising renewable technology to their investors and a hope for the global warming elimination with its massive application. However decisions for massive applications in this technology should follow a successful operating Floating Solar Chimney SAEPP model of several MW.

Appendix I

The fundamental equation for the operation of the SAEPP i.e. the electric Power Output P as function of the moving air mass flow $\dot{m}$ has been derived by the author in ref [4] .A presentation of the results of this analysis is given below.

The derived equation is the following:

$$P = C_p \cdot \dot{m} \cdot \left(T_{03} - C_1 - T_4 - C_2 \cdot T_4^{\,2}\right) \quad (4)$$

Where T_{03} is the entrance stagnation air temperature in the air turbines and $\dot{m}$ the warm air mass flow in Kg/sec. T_{03} is also the exit air temperature by the solar collector, thus can be defined exclusively by the solar collector thermal analysis. An approximate procedure for T_{03} calculation is given by Shlaigh in ref [1] . In this analysis an approximate equation relating the exit solar collector air temperature T_{03} to its input air temperature T_{02} valid for the circular Solar Collector is given by:

$$ta\cdot G\cdot A_c = \dot{m}\cdot C_p\cdot(T_{03} - T_{02}) + \beta\cdot A_c\cdot(T_{03}-T_{02}) \quad (5)$$

β is the approximate thermal losses coefficient of the Solar Collector per m^2 and ^0C of the temperature difference (T_{03}-T_{02}) . An average value for β, for double glazing, is ~4 $W/m^2\,^0C$ (for single cover solar collectors β≈10 $W/m^2\,^0C$).

G is the operating irradiance on a horizontal surface of the Solar Collector. The average operating G for a SAEPP operating 8760 hours per year due to ground thermal storage is the annual solar irradiation on the horizontal surface of the solar collector (per m^2) divided by the 8760 hours of operation, while the maximum G is approximately calculated dividing by 3000 hours. The coefficient ta is the average of the product: {roof transmissivity for solar irradiation × collector soil absorptivity for solar irradiation}. An average value for the coefficient ta, for double glazing, is ~ 0.75(for single cover solar collectors ta≈0.81 $W/m^2\,^0C$). A_c is the Solar Collector's surface area.

Thus an approximation for the function T_{03} ($\dot{m}$), necessary for the SAEPP's power calculation is:

$$T_{03}(\dot{m}) = [\, ta\cdot G / (\beta + \dot{m}\cdot C_p/A_c) \,] - T_{02} \quad (6)$$

Where T_{02} is approximately equal to the ambient temperatureT_0 plus 1 ^oC (due to ground thermal storage around the Solar Collector). In ref. [10] was presented a more accurate thermal analysis for T_{03} calculation, however for reasonable estimations about thermal coefficients of the solar collector, the T_{03} calculated values using this more accurate method are small, hence the approximation (6) can be used for an initial SAEPP's dimensioning analysis.

T_4 is the appropriate root of the polynomial equation: $w_1 T_4^4 + w_2 T_4^3 + w_3 T_4^2 + w_4 T_4 + w_5 = 0$ (7)

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

$$w_1 = C_2^2 (1-k) \qquad w_2 = C_2 \left(2 - k - n_T C_2 T_4'\right)$$

$$w_3 = C_2 C_3 (1-k) + 1 - 2 n_T C_2 T_4'$$

$$w_4 = C_3 - n_T T_4' (1 + C_1 C_2) \text{ and } w_5 = -n_T T_4' C_1,$$

where C_1, C_2, C_3, T_4' are given by:

$$C_1 = g \cdot H / C_p$$

$$C_2 = a \cdot (R \cdot \dot{m} / (A_{ch} \cdot p_4))^2 / (2 \cdot C_p)$$

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

$$T_4' = T_{03} \cdot (1 - C_1 / T_0)$$ and

$$A_{ch} = \pi \cdot d^2 / 4 \qquad p_4 = p_o (1 - C_1 / T_0)^{3.5},$$

R=287J/Kg ^{0}C, g=9.81 m/sec^2 and C_p=1005 J/Kg ^{0}C.

p_o is the ambient atmospheric pressure, η_T is the overall efficiency of the Air Turbines and Generators, k is the FSC's friction loss coefficient and α its kinetic energy correction coefficient .

Average values for T_0 and p_0 are T_0=(273.2+25) ^{0}K and p_0=103200 Pa. Usual value for a is 1.1058.

An average value for η_T is 0.8, for a well-designed Air Turbine operating around its optimum point of operation. An average value for k for a reasonable internal diameter choice is given by the formula: k=0.5+0.5·H/3000 (8).

The necessary data for the calculation of Electric Power Output as function of mass flow $\dot{m}$ are the following figures:

The annual solar irradiation on horizontal surface Wy (in KWh/m^2)

An approximate value for maximum Power Rating (P_R in KW) calculations is given by:

G_{AV}=Wy/3000 hours

H= FSC's height in m

d= FSC's internal diameter in m

D_c= Solar Collector's outer diameter in m.

The annual energy production is approximately equal to Ey≈P_R·3000 KWh

The diameter d_{rt} of the N_{rt} Air Turbines is calculated approximately by the formula:

$d_{rt} = 0.9 \cdot d / \sqrt{N_{rt}}$ (9), considering that the air speed inside the solar chimney and at the output of the air turbines' diffusers should be the same.

The entrance height in the outer diameter of Solar Collector is ~2÷3 m, the inner height of it is higher than 1.1· d_{rt}.. In an inner wall higher than 1.1·d_{rt} the N_{rt} Air Turbines are placed with horizontal axis, geared to their respective Induction Generators, around the Floating Solar Chimney. This inner wall should have a diameter bigger than 1.1·(d_{rt}·N_{rt})/π.

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