Solar chimney technology without solar collectors

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1 Introduction

The solar chimney technology is an electricity generating solar thermal technology, experimentally tested. The experimental results analysis and data were presented by J. Schlaigh in his book [1].
The operation of the solar chimney technology is based on the exploitation of two physical atmospheric phenomena using a set of artificial structures and electromechanical machines.
The first atmospheric phenomenon is the reaction of the heated ground by the solar irradiation. The temperature of the heated ground is increased and the ground sends back to space part of the received thermal energy by infrared radiation. The convection to atmosphere of the warm air in touch to the ground also helps the ground to transmit thermal energy and to maintain the thermal equilibrium to the received thermal power by the solar irradiation in a proper temperature.
These thermal emitting processes will be decelerated if the ground is covered by a glass roof greenhouse. The glass is transparent to solar irradiation but opaque to thermal radiation of lower frequency. Also the roof of the greenhouse limits the development of the air convection. As a result the temperature of the ground below the greenhouse is increased in order the thermal equilibrium to be achieved for the received thermal power by solar irradiation.
The second atmospheric physical phenomenon is the chimney effect i.e. the creation of an up-drafting warm air stream though a tall chimney due to the warm air buoyancy around the bottom of the chimney.
Thus placing a solar chimney in the centre of the previous greenhouse which is open in its periphery, a steady up-drafting stream of warm air through the chimney will be created.
The up-drafting power of warm air will be proportional to the temperature gain ΔT of the moving stream of air above the heated ground from the open periphery of the greenhouse to the bottom of the solar chimney. It will also be proportional to the solar chimney height H.
Placing a set of air turbines engaged to proper electric generators, part of the thermodynamic power of the up-drafting stream of warm air can be transformed to electricity.
The previously described process is referred as solar chimney technology.
The major structures of the solar chimney technology are the greenhouse (solar collector) and the solar chimney.
The electromechanical machines of the solar chimney technology are air turbines, electric generators and gear boxes or electronic devices that are used in order to match the air turbine rotation frequency f_T and the electric generator voltage to the grid frequency f and voltage.
By the description it is evident that the existence of the solar collector is requisite for the solar chimney technology operation.
In the described solar chimney theory the ground was considered dry, because if the ground is wet or partly covered by plants or waters, the water evaporation and the plants' transpiration will absorb part of solar irradiation due to latent heat phenomena, so the increase of ground temperature ΔT due to solar irradiation will be smaller than expected.
Furthermore on the description of the solar chimney technology we did not take into consideration the air humidity phenomena considered them as of a marginal effect on the solar chimney technology operation.
As we will show in the paragraph 3 the air humidity effect under certain conditions could be the primer air up-drafting generator, thus the greenhouse and its relative air up-drafting operation can be omitted.
The solar chimney technology without solar collectors was also proposed by Denis Bonnelle http://www.solar-tower.org.uk/equatorial-bonnelle.php

2 An approximate analysis for the operation of the solar chimney technology

The moving up-drafting air mass though the solar chimney in Kg/sec is symbolized by $\dot{m}$. Its temperature increase from the open periphery of the greenhouse to the bottom of the solar chimney is ΔT.

Thus the quantity $\dot{m} \cdot c_p \cdot \Delta T$ is the increase of the up-drafting air mass thermodynamic power due to greenhouse operation where c_p is the isobaric specific heat of the air ~1005 Joule/Kg·^{0}K.

In average this thermodynamic power is proportional to the annual average horizontal solar irradiation on the roof of the solar collector given by the formula $A_c \cdot w_y / 8760$, where w_y is the annual horizontal solar irradiation in the place of installation of the solar collector in Kwh/m^{2}y and A_c is the solar collector surface area in m^2,

i.e. $\dot{m} \cdot c_p \cdot \Delta T / 1000 = \eta_{gr} \cdot (A_c \cdot w_y / 8760)$ in KW (1)

where η_{gr} is the greenhouse efficiency.

The greenhouse efficiency is approximately 50% for a double glazing roof greenhouse and 33% for a single glazed roof greenhouse.

This thermodynamic power without intermediate air turbines is transformed into kinetic power in the exit of the solar chimney plus friction losses on the wall of the solar chimney. Without any friction losses the kinetic power of the air mass adiabatically rising inside the solar chimney will be equal to the product of the input thermodynamic energy in the bottom entrance of the chimney $\dot{m} \cdot c_p \cdot \Delta T$ and the Carnot efficiency, that is equal to the ratio of the decrease of the temperature of the up-drafting air $g \cdot H / c_p$ where g is the gravity constant 9.81 m/sec^2 and H the chimney height in m, divided by the ambient temperature T_0 in ^{0}K.

Thus the maximum kinetic power at the top exit of the solar chimney should be

$$P_{\max} = (\dot{m} \cdot c_p \cdot \Delta T) \cdot (\frac{g \cdot H}{c_p \cdot T_0}) = \dot{m} \cdot g \cdot H \cdot \frac{\Delta T}{T_0} \quad \text{in W} \quad (2)$$

Let us calculate approximately the top exit air speed in the solar chimney.

The maximum power generated by the up-drafting solar chimney operation is transformed into kinetic mechanical power in the top exit of the chimney plus the friction losses in its internal wall, that is proportional to the exit kinetic power,

$$\text{Thus: } P_{\max} = a \cdot (1+k) \cdot \frac{1}{2} \dot{m} \cdot \upsilon^2 \quad \text{in W} \quad (3)$$

where α= kinetic energy correction coefficient and k=solar chimney friction loss coefficient (usual average values of a and k are respectively 1.1058 and 0.5).

Thus the top exit maximum air speed is given by:

$$\upsilon = \sqrt{2 \cdot \mathrm{g} \cdot \mathrm{H} \cdot \frac{\Delta T}{T_0} / [(k+1) \cdot a]} \quad \text{in m/sec} \quad (4)$$

When the air turbines are operating in their optimal point of operation it can be proved that the exit air speed is approximately 40÷50% of the top maximum air speed. This comes about because ΔT depends also on the mass flow.

When the air turbines placed in the path of moving stream of air are operating they receive the major part of this up-drafting kinetic power and through the respective electric generators transform it to electricity.

Thus the average electric power in KW should be:

$$P_{El,Av} = \eta_T \cdot \eta_{CH} \cdot (\frac{\dot{m}_{AV} \cdot c_p \cdot \Delta T_{AV}}{1000}) \cdot (\frac{g \cdot H}{c_p \cdot T_0}) = \eta_T \cdot \eta_{CH} \cdot \eta_{gr} \cdot (\frac{w_y \cdot A_c}{8760}) \cdot (\frac{g \cdot H}{c_p \cdot T_0}) \quad (5)$$

Where: η_T is the air turbine electric generators combined efficiency ~ 80% and η_{CH} is the friction and the top exit kinetic losses of the chimney ~ 90%.

And the annual electricity generated by the solar chimney power plant is equal to:

$$W_y = \eta_T \cdot \eta_{CH} \cdot \eta_{gr} \cdot (w_y \cdot A_c) \cdot (\frac{g \cdot H}{c_p \cdot T_0}) \quad \text{in KWh} \tag{6}$$

For an average T_0=293.2 ^{0}K, the annual electricity generation of a reasonably designed solar chimney power plant with a double glazed greenhouse is approximately given by the relation:

$$W_y = 1.2 \cdot H \cdot w_y \cdot A_c / 10^5 \quad \text{in KWh} \tag{7}$$

Thus the main results that came about by the previous analysis are:

- The top air speed at the exit of the solar chimney is proportional to the square roots of the temperature increase ΔT, generated by the solar collector operation due to solar irradiation and the chimney height H.
- The electric power generated by the solar chimney power plant is proportional to the temperature increase ΔT, and the chimney height H.
- The annual electric energy generated by the solar chimney power plant is proportional to the solar collector surface area A_c and the chimney height H.

The previous approximate analysis was made considering the air dry (zero humidity) and was based on previous information given in the following references [1,2,3,4,5,6]

3 The air humidity effect on solar chimney operation

In order to study the effect by the humidity of the up-drafting air mass $\dot{m}$ inside the solar chimney the following should be taken into consideration:

- The saturated air has the maximum water vapour density d_s measured in gr/Kg of air.
- The unsaturated air is characterized by its relative humidity RH and its water vapour density is given by the product RH·d_s
- The value of d_s is defined by the partial water vapour pressure p_w and the ambient pressure p by the relation:

$$d_s = 622 \cdot \frac{p_w}{p - p_w} \quad \text{in gr/Kg of air} \tag{8}$$

  Where: 0.622 is the ratio of molecular masses of water to air.
- The partial pressure of water vapour is a function of the temperature t in ^{0}C and is given by the Arden Buck approximate equation:

$$p_w = 611.21 \cdot \exp\left(\frac{(18.678 - t/234.5) \cdot t}{257.14 + t}\right) \quad \text{in Pa, for } -80^0\text{C} < t < +50^0\text{C}. \tag{9}$$

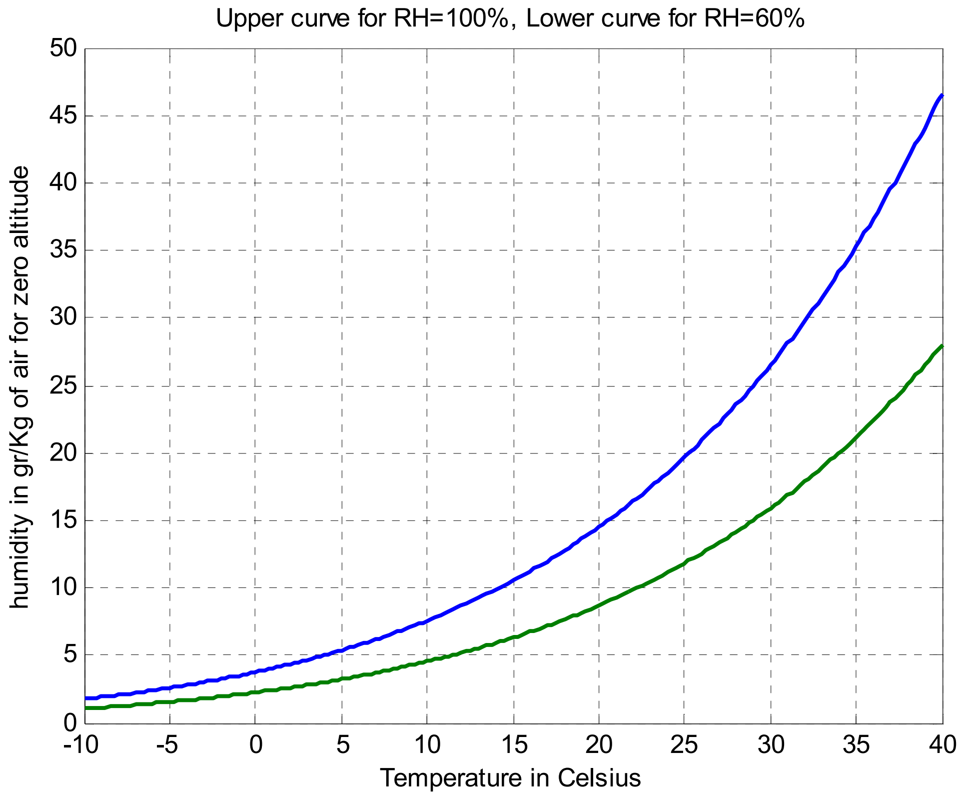
- The temperature and the pressure of the adiabatically up-drafting air mass inside the chimney are functions of altitude z as follows:

$$T(z) = T_0 - \frac{g \cdot z}{c_p} \ , \ p(z) = p_0 \cdot \left(T(z)/T_0\right)^{3.5} \tag{10}$$

  Where: T_0=ambient temperature in^{0}K in the bottom of the chimney and p_0=ambient pressure at the altitude of the bottom of the chimney, if no data existp_0≈103200 Pa for zero altitude.
- The latent heat for water vapour evaporation is L=2257 J/gr so the humid moving air mass $\dot{m}$ contains thermal power equal to:

$$P_{th,L} = \dot{m} \cdot (RH \cdot d_s \cdot L) \text{ in W} \tag{11}$$

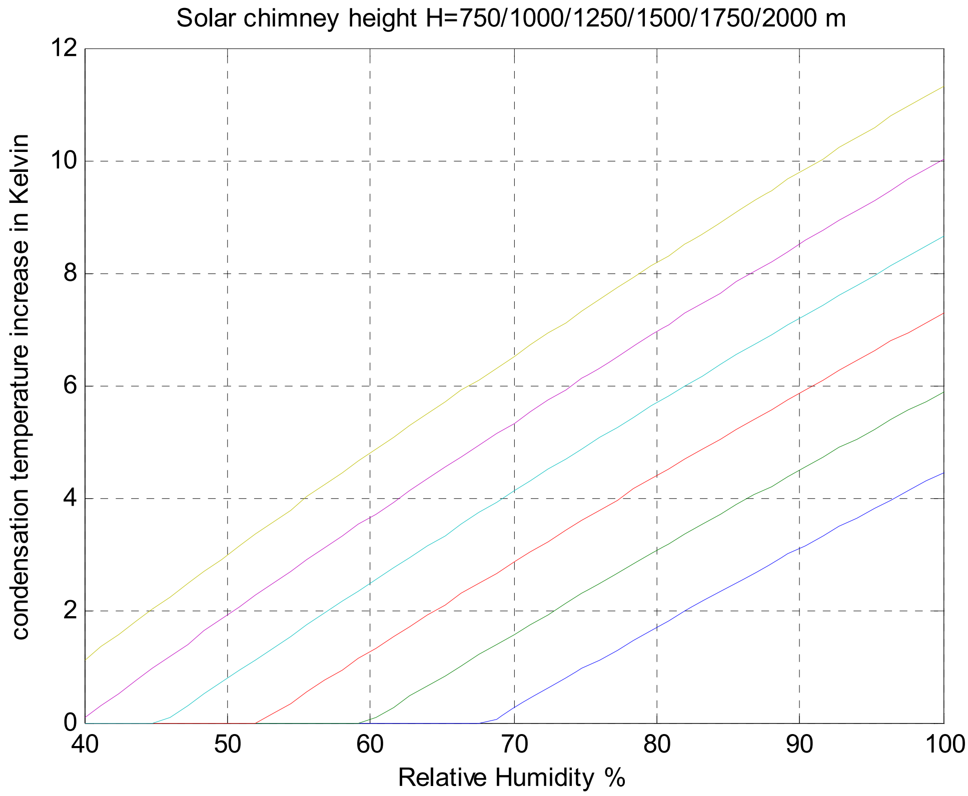
When the water vapour is condensed, thermal power is given to the air increasing its temperature.
The following figure shows the humidity as function of ambient temperature of the air in an ambient pressure p_0=103200 Pa for two values of relative humidity.



Using the previous theoretical analysis and equations we can analyse the humidity effect on the up-drafting air mass inside the solar chimney with its bottom air relative humidity RH thus of a humidity RH•$d_{s,0}$ in gr/Kg of air.
As the humid air is up-drafting its temperature and pressure are decreasing thus its saturated maximum humidity is decreasing and in the top exit is $d_{s,H}$. If this is smaller than the initial humidity in the bottom RH•$d_{s,0}$ a part of the water vapour in the up-drafting air mass is condensed. The condensed water vapour density d_{cond} is the difference (RH•$d_{s,0}$- $d_{s,H}$), taking into consideration the increase into the temperature of the up-drafting air mass due to the condensation.
As a result a latent heat power in order to add to the up-drafting air mass its relative humidity should be high in the bottom of the chimney (in order RH•$d_{s,0}$ to be bigger) and the solar chimney should have adequate height (in order $d_{s,H}$ to be smaller).
If the condensed mass in gr/Kg of the air mass is d_{cond} the temperature increase offered in the up-drafting air mass should be:

$$\Delta T_{cond} = d_{cond} \cdot L / c_p \approx 2.25 \cdot d_{cond} \qquad (12)$$

This temperature increase should be added to the temperature increase ΔT_{gr} due to the greenhouse temperature increase from the periphery of the greenhouse to the bottom of the solar chimney.
Thus in order to take into consideration the air humidity effect in the equations of the previous paragraph ΔT should be taken as $\Delta T=\Delta T_{gr}+\Delta T_{cond}$.
In the following figure ΔT_{cond} is given as function of the solar chimney height H for various bottom relative humidity values. The code for the production of the figures was based on the previous equations.
The ambient bottom temperature was taken equal to an average value of 20^0C and the pressure 103200 Pa. For example as it is shown by the figures the minimum solar chimney height for humidity effects for bottom relative humidity 60% is 1000m.



Thus considerable humidity effects are appearing for solar chimneys much taller than 1000m for ground relative humidity higher than 60%. In this way, in a specially chosen place of high annual average humidity, say RH=70% for example, a solar chimney of 1500m height could operate without a solar collector with a driving average temperature increase of ΔT_{cond} ≈4.1 ^{0}C.

When ΔT is independent of the mass flow, as it is in the case of solar chimney operation due to latent heat of water vapor condensation,it can be proved that the optimum operation of maximum power output will be achieved when the air speed is related to the maximum air speed by the relation: $\upsilon_{opt} = \upsilon_{\max} / \sqrt{3}$. However in this case the chimney losses become 20% and the η_{CH}≈0.8

By equation (3) the maximum air speed inside the chimney would be equal to ~16.5m/sec, and for an internal diameter d=75m and an air density of 1.226 Kg/m^3 and an operating air speed of ~9.5m/sec the average up-drafting air mass will be $\dot{m}$ ≈51450Kg/sec. Using the first part of equation (5) for η_T=0.8 η_{CH}=0.8 the average electrical power of this solar chimney power plant will be equal to ~7.0 MW.

Considering an average annual operation of 8000 hours with an average humidity of 70% (the rest 765 hours of the year the humidity is considered lower than 45%),its annual electricity generation should be equal to 56 GWh/year. The rating power should be calculated for RH=100% thus for ΔT_{cond} ≈8.7 ^{0}C. Thus by equation (3) the maximum air speed inside the chimney would be equal to ~24m/sec, and for an internal diameter d=75m and an air density of 1.226 Kg/m^3 and an operating air speed of ~13.0m/sec the average up-drafting air mass will be $\dot{m}$ ≈70000Kg/sec. Using the equation (5) for η_T=0.8 η_{CH}=0.8 the maximum electrical power of this solar chimney power plant i.e. its rating power will be equal to ~21 MW.

This power plant was considered to be installed in a specially chosen place of high humidity, near the sea for example, where the annual average relative humidity was ~70% and the maximum 100% while the power plant was operating for 8000h. This solar chimney power plant should be accompanied by a small solar collector just for initiating the up-drafting operation.

4 Floating solar chimneys and proper places for stand alone floating solar chimney power plants

By the previous example it is evident that the latent heat of the humid ambient air can be used in order to generate electricity with solar chimney technology? without the use of solar collectors.
However the use of concrete solar chimneys without solar collectors as of their high cost will make the technology very expensive.
This means that when concrete chimneys are used it is better to be combined by huge solar collectors that are generating $\Delta T_{gr} \gg \Delta T_{cond}$. In the case of solar chimney technology without solar collectors the proper solution is to use the low cost alternatives of the concrete solar chimneys as are the floating solar chimneys (FSC) see the site www.floatingsolarchimney.gr .
In fact the construction cost of the concrete solar chimneys of height above 1000m is not less than π·d·H·600 (EUROs) while the respective FSCs have an estimated construction cost of π·d·H·20 (EUROs) i.e a cost 30 times smaller.
For the previous example the FSC of 1500m and 75m diameter should have a construction cost of ~8 million EUROs. If we add a cost of 12 million EUROs for the air turbines electric generators and the small solar collector, we have a construction cost of 20 million EUROs while its production is 56 GWh.
So the capital cost of this renewable investment is ~0.36 EURO/KWh. This is an extremely low figure. For example the capital cost of an inshore wind turbine is not less than 0.55 EURO/KWh while the cost of the offshore wind turbine is not less than 0.7 EURO/KWh.
The average annual humidity in appropriate places around the globe can be as high as 20gr/Kg. In such places where could be cloudy and of a small average solar irradiation the tall floating solar chimneys without solar collectors can be the proper choice for electricity generation using the solar chimney technology. However the proposed technology should be experimentally tested.
If the technology could be proved operating as the proposed theory, it could be a new window of opportunity for places of high annual average relative humidity and without adequate solar irradiation or appropriate land-fields.
The structural integrity of the tall floating solar chimneys against external winds is a serious challenge that can be solved by proper engineering and technology applications. The handling and maintenance procedures for these fabric structures can be established as experience will be accumulated.
The potential of this atmospheric technology is huge considering that the water vapor in the atmosphere is 12900 Km^3 equivalent to the latent heat energy of $8.13 \cdot 10^6$ TWh and this water vapor although is falling as precipitation snow etc. it is continuously regenerated though the water evaporation and the plants transpiration due to the solar irradiation.
In general the best places for floating solar chimney technology without solar collectors operating due to humidity are places near the seas and most probably in equatorial parts of all the continents where the average annual humidity could be higher than 18gr/Kg.
There were pioneering ideas proposing to make artificial lakes with sea water below standing alone solar chimney power plants, or around their small solar collectors in order to increase the local relative humidity and generate electricity and in several cases either desalinated water or humid plumes above them, beneficial for the local climate of areas around the solar chimneys.
The generation of humid plumes above solar chimney power plants, placed in humid areas, has been recently studied by Xinping Zhou et al in the paper [7].

5 Solar chimney dehumidifiers for desalination and electricity generation

In a recent paper [8] Xinping Zhou et al have proposed special dehumidifiers in order to remove the water and to produce desalinated water plus electricity. However they assume the dehumidifiers to be placed near the top exit of the chimneys, thus the solar chimneys

should be concrete and at the same time very expensive. The writers neither propose any specifications or rough ideas about the technology of the dehumidifier nor the way that the dehumidifier operates and so the up-drafting air mass is not blocked.
On the contrary B.A. Kashiwa et al in a paper [9] propose a specific dehumidifier operating though the cyclone effect in the bottom entrance of the solar chimney that looks operative but not yet tested. The cyclone dehumidifiers can be combined with floating solar chimneys and if proven operative could form an extremely low cost atmospheric machine generating electricity and or fresh water.
I sincerely hope that field tests on this promising technology will be possible to be executed as soon as possible.

References

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