Modular Units II for Solar Electricity Large Scale using Natural Convection

Summary

A simple configuration is described for harnessing solar energy using natural convection. A solar collector and warm air store of modest height generate a buoyancy force which draws ambient air through the configuration. Incoming air is required to pass through a convergent-divergent nozzle where it is accelerated to high velocity. A turbine sited at the throat of the nozzle intercepts this kinetic energy of airflow generating electricity. A laboratory model (1 x 1 x 1.5 m) is described for which earlier CFD studies gave promising results [1]. Readers are asked to build an apparatus for experiment to improve on earlier results and to develop the model. If such work is successful, theoretical calculations are presented for a field scale prototype (solar collector 10 x 10 m) and for a large scale Modular Unit (100 x 100 m). Such Modular Units could be built in repeat patterns on desert or arid land in hot climates to generate an average of over 80 MW/km^2.

Introduction

It is self evident that the ideal solution to the world energy problem and to global warming would be the direct, efficient harnessing of solar energy. Enormous progress has been achieved in recent decades in the technologies of solar hot water systems, photovoltaics and concentrated solar power (CSP) for electricity generation.

The solar chimney provides a possible technology for harnessing solar energy large scale using natural convection but progress has been slow because of the very tall chimney needed (up to 1000m) and its low efficiency (under 3%). The present author has drawn up several proposals for harnessing solar energy using natural convection and published these on this website. The present proposal relates most closely to earlier entries titled ‘Buoyancy Driven Solar Engine’ (May 2008) and ‘Modular Units for Solar Electricity Large Scale using Natural Convection’ (March 2013).

Theoretical Development

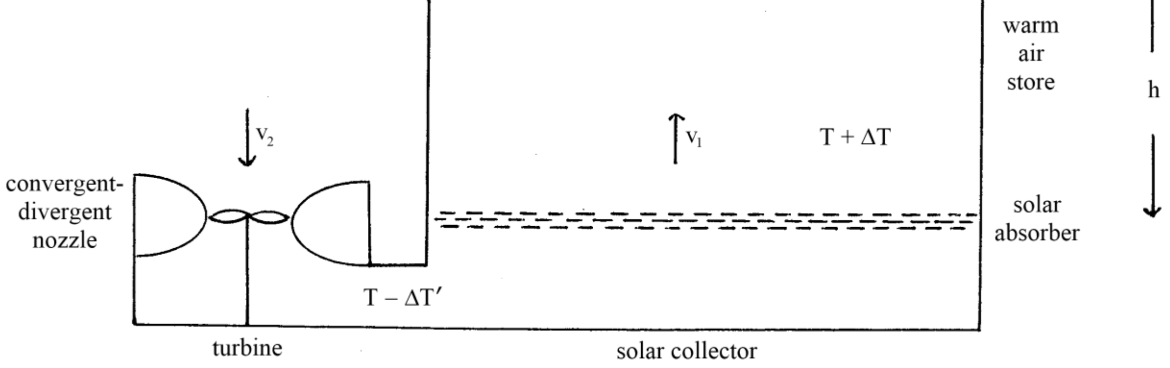

Figure 1

Consider the configuration in Figure 1. The major feature is a large glass solar collector and warm air store. The solar absorber is multi layered and of very open construction to allow easy air flow.

As the absorber takes up solar energy it warms air in its immediate neighbourhood which rises because of its lower density. A convection current is set up where warm air leaves the warm air store via the flap valve which safeguards against reverse flow.

Ambient air is drawn into the configuration through the convergent-divergent nozzle and turbine. The throat of the nozzle has a small cross-sectional area so the incoming air is accelerated to a high velocity. The turbine intercepts and exports a high proportion of this flow kinetic energy generating electricity but causing a fall in temperature for the incoming air. The solar absorber then warms the incoming air to above ambient temperature for flow into the warm air store and then into the atmosphere.

Consider

A_1	area solar absorber
A_2	area throat of nozzle
h	height warm air store
v_1	velocity of air flow through warm air store
v_2	velocity of air flow through throat of nozzle
T	ambient temperature
ΔT	excess temperature (above ambient) of warm air store
$\Delta T'$	fall in temperature of incoming air caused by turbine
g	gravitational constant
C_p	heat capacity of air at constant pressure at temperature T
ρ	density of air at temperature T and atmospheric pressure
I	insolation

The warm air store of height h contains air at a temperature T + ΔT. The velocity of air flow through the absorber and warm air store is given by the solar chimney equation [2, 3]

$$v_1^{\,2} = 2 \frac{\Delta T}{T} g h \qquad (1)$$

Constant mass flow requires that

$$\begin{array}{c} \text{mass flow through} \\ \text{warm air store} \end{array} = \begin{array}{c} \text{mass flow through} \\ \text{throat of nozzle} \end{array}$$

$$A_1 v_1 \rho = A_2 v_2 \rho$$

$$A_1 v_1 = A_2 v_2 \qquad (2)$$

Ambient air is accelerated from rest to velocity v_2 as it is drawn into the throat of the nozzle. The gain in flow kinetic energy comes from the internal energy (enthalpy) of ambient air and causes a fall in its temperature ΔT′.

$$\begin{array}{c} \text{kinetic energy of air flow} \\ \text{in throat of nozzle} \end{array} = \text{mass flow x heat capacity x fall in temperature}$$

$$\tfrac{1}{2} \dot{m} v_2^{\,2} = \dot{m} C_p \Delta T'$$

where ṁ is the mass flow

$$v_2^{\,2} = 2 C_p \Delta T' \qquad (3)$$

It is assumed that the turbine absorbs the kinetic energy of the air flow with high efficiency and exports this as electricity. The air flow enters the solar collector at a temperature $T - \Delta T'$ but leaves at a temperature $T + \Delta T$

solar energy taken up by absorber = mass flow x heat capacity x temperature rise

$$I A_1 = \rho A_1 v_1 C_p (\Delta T + \Delta T')$$

$$I = \rho v_1 C_p (\Delta T + \Delta T') \qquad (4)$$

The values of T g C_p ρ and I are known whilst A_1 A_2 h v_1 v_2 ΔT and $\Delta T'$ are variables. We have 4 equations and 7 variables. If three of the latter are fixed the other 4 variables can be calculated.

Laboratory Model

Consider building a laboratory model as in Figure 1 where

A_1	1 x 1 m
h	1.5 m

Consider that for this model, the cross-sectional area of the throat of the nozzle is such that $\Delta T = \Delta T'$ giving 50% overall efficiency for the conversion of solar energy into electricity. Consider

T	300°	K
g	9.81	ms^{-2}
C_p	1005	$j\ kg^{-1}\ K^{-1}$
ρ	1.18	$kg\ m^{-3}$
I	750	$w\ m^{-2}$

The value for insolation I = 750 represents maximum UK summer insolation.

From equations (1) and (4) eliminate v_1

$$\left[\frac{I}{\rho C_p (\Delta T + \Delta T')}\right]^2 = \frac{2\,\Delta T\, gh}{T}$$

$$\left[\frac{I}{2\rho C_p \Delta T}\right]^2 = \frac{2\,\Delta T\, gh}{T}$$

$$\Delta T^3 = \frac{T I^2}{8\rho^2 C_p^2 gh}$$

$$= \frac{300 \times 750 \times 750}{8 \times 1.18 \times 1.18 \times 1005 \times 1005 \times 9.81 \times 1.5}$$

$$= \frac{168.75 \times 10^6}{165.56 \times 10^6}$$

$$= 1.01929$$

$$\Delta T = 1.0064\ ^\circ C$$

From (3) $v_2^{\,2} = 2 \times 1005 \times 1.0064$

$v_2 = 44.98\ \mathrm{ms^{-1}}$ (100mph)

From (4) $v_1 = \dfrac{750}{1.18 \times 1005 \times 2 \times 1.0064} = 0.3142\ \mathrm{ms^{-1}}$

From (2) $A_2 = \dfrac{1 \times 1 \times 0.3142}{44.98} = 0.00699\ \mathrm{m^{-2}}$

This gives a throat of nozzle diameter of 0.0943 m = 9.43 cm

CHECK

Insolation = $I\,A_1$ = 750 watts

Kinetic energy airflow in throat of nozzle = $\tfrac{1}{2}\,\rho\,A_2\,v_2^{\,3}$

$= \dfrac{1.18}{2} \times 0.00699 \times (44.98)^3$

= 375 watts

Heat energy lost from warm air store = $\rho\,A_1\,v_1\,C_p\,\Delta T$

$= 1.18 \times 1 \times 1 \times 0.3142 \times 1005 \times 1.0064$

= 375 watts

This confirms the internal consistency of the calculation with the dimensions devised to give an overall efficiency of 50%.

The work of Premkumar and Ramachandran

A laboratory model as described above was studied by Premkumar and Ramachandran [1]. The dimensions of their model were $A_1 = 1 \times 1$ m, h = 1.5 m, nozzle throat diameter 0.1 m, insolation maximum 1000 $\mathrm{wm^{-2}}$. This gives a theoretical maximum velocity of airflow through the throat of the nozzle of 70 $\mathrm{ms^{-1}}$.

Computational Fluid Dynamics analysis using ANSYS software gave promising results. The authors say that, “The maximum velocity of air obtained at the throat of the nozzle in the CFD analysis is about 50 to 70 m/s which almost resembles the value obtained by theoretical calculation for 100% efficiency.”

A laboratory model was built of the above dimensions and a digital anemometer used to measure airflow velocity through the throat of the nozzle. Experimental results were however “disappointing” with a maximum airflow velocity of 22 m/s at peak insolation.

The present author is convinced however, that the disappointing results were due to the use of several layers of solar absorber at a considerable distance apart (Figure 3 of reference [1]). This had the effect of reducing the effective height of the warm air store to less than 0.5 m. The experimental work needs to be repeated with the absorber accurately as in Figure 1 above.

The work of Premkumar and Ramachandran gave very encouraging CFD results but only modest experimental results but which can be improved. They do however provide outstanding proof of concept.

Field Scale Prototype

On the assumption that a laboratory model constructed as in Figure 1 will give experimental results in line with theoretical predictions, the next step would be to construct a field scale prototype. Consider a configuration where

$$A_1 = 10 \times 10 \text{ m}$$

$$h = 2 \text{ m}$$

$$\Delta T = \Delta T' \quad \text{to give 50\% overall efficiency}$$

As previously

$$\Delta T^3 = \frac{T I^2}{8 \rho^2 C_p^2 gh}$$

$$= \frac{300 \times 750 \times 750}{8 \times 1.18 \times 1.18 \times 1005 \times 1005 \times 9.81 \times 2}$$

$$= 0.7645$$

$$\Delta T = \Delta T' = 0.9144$$

From equation (3) $$v_2^{\,2} = 2 \times 1005 \times 0.9144$$

$$v_2 = 42.87 \text{ ms}^{-1} \text{ (96 mph)}$$

From (4) $$v_1 = \frac{750}{1.18 \times 1005 \times 2 \times 0.9144}$$

$$v_1 = 0.3458 \text{ ms}^{-1}$$

From (2) $$A_2 = \frac{10 \times 10 \times 0.3458}{42.87} = 0.8067 \text{ m}^2$$

This gives a throat of nozzle and turbine diameter of 1.014 m.

CHECK

Insolation $= I A_1 = 750 \times 10 \times 10 =$ 75 kilowatts

Kinetic energy airflow through turbine $= \frac{1}{2} \rho A_2 v_2^{\,3}$

$$= \frac{1.18}{2} \times 0.8067 \times (42.87)^3$$

$$= 37.5 \text{ kw}$$

Heat lost through warm air store $= \rho A_1 v_1 C_p \Delta T$

$$= 1.18 \times 10 \times 10 \times 0.3458 \times 1005 \times 0.9144$$

$$= 37.5 \text{ kw}$$

This demonstrates the internal consistency of the calculations and confirms 50% overall efficiency.

Modular Units II for Large Scale Solar Electricity using Natural Convection

Assuming successful results for the prototype described above, modular units for large scale generation could have dimensions

$A_1 = 100 \text{ x } 100 \text{ m}$

$h = 10 \text{ m}$

$\Delta T = \Delta T'$ again to provide 50% overall efficiency

As previously

$$\Delta T^3 = \frac{T I^2}{8 \rho^2 C_p^2 gh}$$

$$= \frac{300 \text{ x } 750 \text{ x } 750}{8 \text{ x } 1.18 \text{ x } 1.18 \text{ x } 1005 \text{ x } 1005 \text{ x } 9.81 \text{ x } 10}$$

$$= 0.1529$$

$$\Delta T = \Delta T' = 0.5347\ ^\circ\text{C}$$

From (3) $v_2^{\,2} = 2 \text{ x } 1005 \text{ x } 0.5347$

$v_2 = 32.78 \text{ ms}^{-1}$ (73 mph)

From (4) $$v_1 = \frac{750}{1.18 \text{ x } 1005 \text{ x } 2 \text{ x } 0.5347}$$

$v_1 = 0.5914 \text{ ms}^{-1}$

From (2) $$A_2 = \frac{100 \text{ x } 100 \text{ x } 0.5914}{32.78}$$

$A_2 = 180.4 \text{ m}^2$

This gives a throat of nozzle and turbine diameter of 15.16 m.

CHECK

Maximum insolation = $I A_1$ = 750 x 100 x 100 = 7.5 Megawatts

Kinetic energy airflow through turbine $= \frac{1}{2} \rho A_2 v_2^{\,3}$

$$= \frac{1.18}{2} \text{ x } 180.4 \text{ x } (32.78)^3$$

$$= 3.75 \text{ MW}$$

Heat loss through warm air store $= \rho A_1 v_1 C_p \Delta T$

$$= 1.18 \text{ x } 100 \text{ x } 100 \text{ x } 0.3458 \text{ x } 1005 \text{ x } 0.9144$$

$$= 3.75 \text{ MW}$$

This again confirms the internal consistency of the calculation and dimensions quoted for 50% overall efficiency.

A sketch of the Modular Unit proposed is shown in Figure 2.

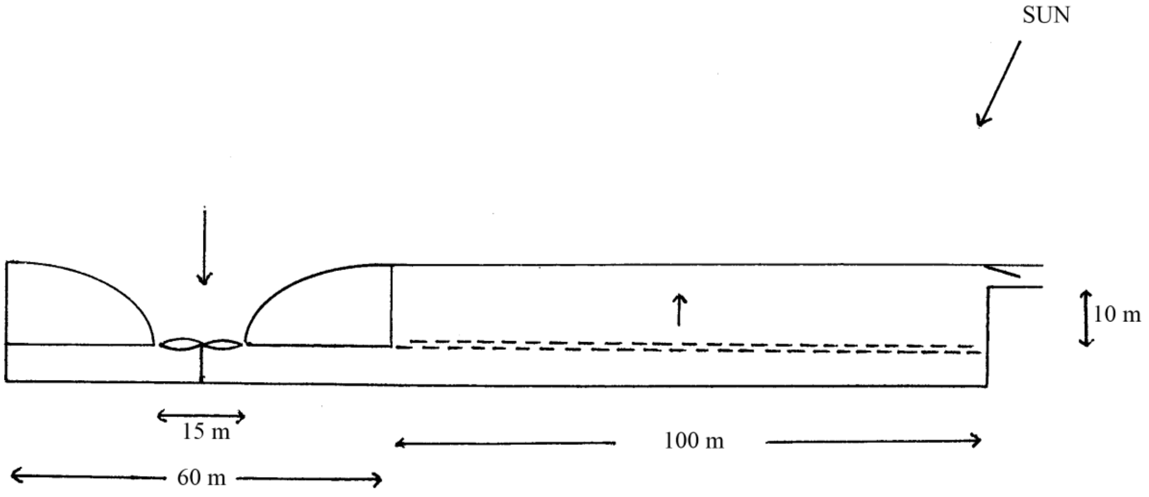

Figure 2

Further Comments

- The solar absorber has a metallic base and its upper surface is coated with highly efficient solar absorber paint. It is suggested that it be multi layered, up to 1 m height and of very open, perhaps honeycomb construction to allow rapid through flow of air.

- Energy storage – water tubes [3] of up to one metre height could be sited on the ground beneath the solar absorber, so that incoming air heats the water to near ambient temperature daytime. This stored thermal energy then provides evening/night generation.

- The plane of the turbine blades should be at the same horizontal level as the solar absorber so that warm air from the absorber rises into the warm air store, setting up a convection current. Flap valves may be required on exit airflow to prevent back flow. If the turbine has high efficiency, the divergent section of the nozzle is unnecessary as indicated in Figure 2.

- The glass or transparent plastic for the solar collector could be double glazed to reduce energy loss.

- Incoming air is drawn vertically downwards from the atmosphere at a level of about 10-20 m above ground. This should minimise dust content.

- Water is only needed for periodic washing of the outer solar collector. There is no water demand for day to day operation. This could be a major advantage over concentrated solar power (CSP) technologies in arid or desert climates.

- The output calculated for the Modular Unit is 3.75 MW at maximum insolation of 750 wm^{-2}. If operating in a tropical climate with average annual insolation of 6 $kWh/m^2/day$ output will average 1.25 MW over 24 hours and 365 days/year.

- The area of the solar collector for the Modular Unit is 10,000 m^2. The nozzle has throat diameter 15 m but since incoming air has to be accelerated to high velocity, the nozzle will need mouth diameter of up to 60 m. The nozzle plus turbine as in Figure 2 has an area 2826 m^2. If Modular Units were constructed in a repeat pattern on desert land, about 70 units/km^2 could be built giving overall average output of over 80 MW/km^2.

- Very Large Scale Modular Units. If the above technology proved successful, it should be possible to build ever larger generating units. Calculations show that for a solar collector of area 500 x 500 m and warm air store height 100 m operating with efficiency 50%, $\Delta T = \Delta T' = 0.2482$ °C, $v_2 = 22.34$ ms^{-1} (50 mph) and $A_2 = 14{,}257$ m^2 giving a turbine diameter of 135 metres. Such a unit would have average output 31 MW.
- None of the above work involves patent applications. The author has no interest in claiming intellectual property rights.

Conclusion

The author believes that the simple configuration described in this paper allows conversion of solar energy into electricity with an overall efficiency of 50%. The laboratory model described has already provided promising CFD results [1] but experimental work needs to be repeated, improved and developed. If successful, the next stage would be to build a field-scale prototype and then a large scale Modular Unit. The ideas involved are low tech and could lead to solar electricity large scale at low cost.

References

1. M Premkumar and S Ramachandran, IEEE Frontiers in Automobile and Mechanical Engineering, 2010, 212-215.
2. L B Mullett, International Journal of Ambient Energy, 8 (1987), 35-40.
3. J Schlaich et al., Journal of Solar Energy Engineering, 127 (2005), 117-124.

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