Modular Units III for Solar Electricity Large Scale using Natural Convection

Summary

A new configuration is described to harness solar energy using natural convection. It has some similarities to the solar chimney but uses the entire solar absorber area for a modest height warm air store. This generates buoyancy which draws ambient air through the solar collector at low velocity. All incoming air is required to flow through a central convergent nozzle where it is accelerated to high velocity. A turbine placed in the throat of the nozzle intercepts this kinetic energy and exports up to 80% of the solar energy absorbed.

Modular units are described of area 100 x 100 m and height 10 m which could be built adjacent to each other in repeat patterns on desert or scrub land generating electricity large scale from solar energy with an overall efficiency of 80% and in a tropical climate an average output of 160 MW/km^2.

Introduction

The world is facing two historic resource and environmental crises:

- the depletion of global oil and gas resources driving up prices and rewarding energy companies for developing ever more contentious sources of fossil fuels eg fracking, tar sands, arctic exploration ...
- the rising levels of carbon dioxide in the atmosphere which have increased from a pre industrial 280 parts per million to the present 400 ppm causing global warming, shrinking glaciers and polar ice and threatening incalculable climate change.

There is no question that the ideal solution to both problems is solar energy if it could be harnessed efficiently and economically. The amount of solar energy reaching the earth is more than 10,000 times world energy demand. If we could harness just 0.01% of incident solar energy that would be energy problem solved, carbon dioxide levels stabilised.

There has been major progress in recent decades in the technologies for solar hot water, photovoltaics and, more recently, concentrated solar power.

The author has always believed that natural convection offers enormous possibilities. It is nature's way of harnessing solar energy; it drives the weather and is the origin of wind and wave energy and hydropower. Convection is one of nature's major processes – in the oceans, in the core and mantle of the earth and in the sun and stars.

But there has been little research on the direct use of natural convection for harnessing solar energy. Solar air collectors have been developed for heating and there is the solar chimney but little else. Exceptionally, Schlaich et al. built and operated a demonstration size solar chimney at Manzanares, Spain in the 1980's [1]. There have been hundreds of theoretical papers on the solar chimney since that time but little practical development. The problem is that the chimney needs a height of up to 1000 metres for an efficiency of just 2%.

The author believes that good efficiency is possible using natural convection in a ground level configuration by including a convergent-divergent nozzle or venturi at a convenient location in the airflow to multiply its velocity. A turbine is then placed in the throat of the nozzle/venturi to intercept the high velocity flow and export its kinetic energy as electricity.

The author has drawn up a series of such proposals and published them on this website [2]. One such proposal was investigated by Premkumar and Ramachandran [3]. Analysis by computational fluid dynamics gave "promising" results but experimental investigation using a laboratory model gave "disappointing" results. Their work, however, provides considerable proof of concept.

Koonsrisuk and Chitsomboon [4] recently published a paper titled "Effects of flow area changes on the potential of solar chimney power plants". They find that a divergent top solar chimney can produce power at the chimney base "as much as hundreds times" that of a reference solar chimney. Indeed an area ratio of 16 for the top of the chimney compared to the base of the chimney "can produce power as much as 400 times that of the reference case."

The present author considers this paper extremely important and its results quite startling. The essential features of the divergent-top chimney are first, that the inverted conical shape provides a large volume of warm air that multiplies the buoyancy force. Second, the base of the chimney is narrow and behaves as a venturi/nozzle multiplying air flow velocity by 16 and its kinetic energy by 256. Indeed, Koonsrisuk and Chitsomboon find that the power at the chimney base is 64.55% of the solar energy absorbed in the collector. There is however no consideration of inserting a turbine into the air flow.

The present author believes that the essential requirements for an efficient solar convection engine are

- a large area solar collector to absorb incident solar energy with high efficiency and produce a flow of warm air.
- a warm air store which can be a chimney or rectangular/cubic space of considerable height and cross-sectional area through which the warm air flows.
- a constriction/venturi/nozzle through which the air flow must pass that multiplies air flow velocity.
- a turbine placed in the throat of the nozzle/venturi which converts the kinetic energy of the flow into electricity.

Based on these principles, a new configuration is now proposed.

Configuration proposed

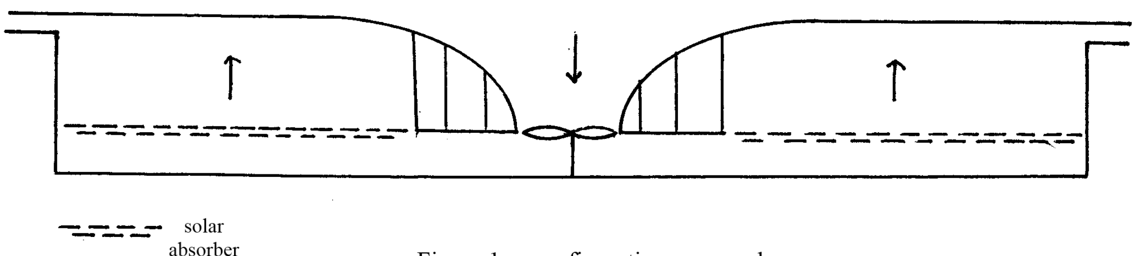

Figure 1 configuration proposed

A solar collector of considerable area has glass roof and sides. The solar absorber is at a raised level, multilayered and abundantly perforated to allow easy air flow. It could be of metallic honeycomb structure coated with absorber paint that allows absorption of incident solar energy with over 90% efficiency. The solar energy absorbed warms air in its vicinity which rises because of its lower density. The volume above the absorber is of considerable height and forms a warm air store. The warm air flows through exit channels which can be fitted with flap valves if necessary to prevent back flow.

The rising warm air draws ambient air from beneath to replace. This in turn is drawn from the atmosphere via the central convergent nozzle. The nozzle will need to be strengthened in its central regions and could be made of metal/steel to withstand the high velocity air flow anticipated. A turbine located at the throat of the nozzle intercepts this flow kinetic energy and exports electricity. This causes a fall in temperature for incoming air before it reaches the absorber. It should be noted that the blades of the turbine should be at the same vertical level as the solar absorber.

At constant insolation, a steady state is reached where the temperature of the warm air store is above ambient and there is a constant air flow through the configuration. **It is the excess temperature (above ambient) and height of the warm air store that generates the buoyancy force that drives the system.**

Theoretical Development

Consider that in Figure 1

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 and 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 $T + \Delta T$. The buoyancy force generated creates an air flow velocity v_1 through the solar absorber and warm air store given by the solar chimney equation [5, 6]

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

Constant mass flow requires that

mass flow through warm air store = mass flow through throat of nozzle

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

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

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 $\Delta T'$.

kinetic energy of air flow in throat of nozzle = mass flow x heat capacity x fall in temperature

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

where $\dot{m}$ 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

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

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

Now let us consider equations (1) to (4) collectively. 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. In this way any number of possible variations can be devised.

Efficiency of conversion of solar energy into electricity

The author believes that the configuration proposed allows generation of electricity from solar energy with very high efficiency. The main energy loss, as with the solar chimney, is through exit air leaving the configuration at an elevated temperature. But it is this very elevated temperature in the chimney/warm air store that creates the buoyancy force that drives the system. This energy loss is unavoidable but it can be reduced by judicious choice of dimensions.

The second major energy loss will be in the turbine. Generally wind turbines in the open air are subject to the Betz efficiency limit of 16/27 or 59%. In this case however, we have a ducted turbine for which an efficiency of over 80% is possible. Also any loss of energy in the turbine is not lost to the system. It will be manifested as heat carried into the warm air store and be effectively recycled contributing to buoyancy.

It is the author's view that for the configuration proposed, overall efficiency could be up to 80%. Indeed, using the theoretical development above, dimensions can be devised to give variations with an efficiency of 1 – 5 – 10 – 20 – 50 – 80%. Low efficiency systems have low height and low velocity of air flow through the turbine. Such systems will be described in a future paper where solar energy can be harnessed using conventional wind turbines as are currently deployed in onshore wind generation. For high efficiency, a greater height is needed for the warm air store and/or higher velocity through the venturi/nozzle and turbine. The modular unit now proposed is devised for an overall efficiency of 80%.

Modular unit proposed

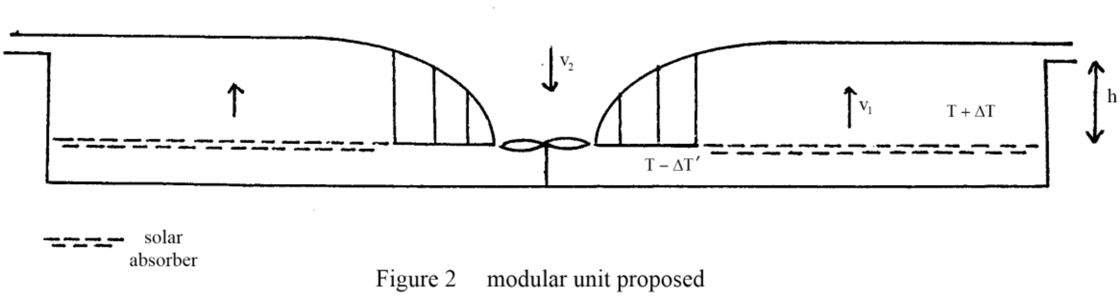

Figure 2 modular unit proposed

Consider

$$A_1 = 100 \times 100 \text{ m}$$
$$h = 10 \text{ m}$$
$$\Delta T' = 4\Delta T \quad \text{to give 80\% overall efficiency}$$

From equation (1) and (4) eliminate v_1

$$\left[\frac{I}{\rho\, C_p\, (\Delta T + 4\Delta T)}\right]^2 = 2\, \frac{\Delta T}{T}\, gh$$

$$\Delta T^3 = \frac{I^2\, T}{50\, \rho^2\, C_p^2\, gh}$$

Consider

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

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

$$\Delta T^3 = \frac{750 \times 750 \times 300}{50 \times 1.18 \times 1.18 \times 1005 \times 1005 \times 9.81 \times 10}$$

$$= 0.02446$$

$$\Delta T = 0.2903° \text{ K}$$

$$\Delta T' = 1.1612° \text{ K}$$

From (3) $$v_2^2 = 2 \times 1005 \times 1.1612$$

$$v_2 = 48.3 \text{ ms}^{-1}$$

From (1) $v_1^{\,2} = 2 \times \frac{0.2903}{300} \times 9.81 \times 10$

$v_1 = 0.4357\ ms^{-1}$

From (2) $A_2 = \frac{100 \times 100 \times 0.4357}{48.3}$

$= 90.2\ m^2$

This gives a throat of nozzle and turbine diameter of 10.7 m.

<u>CHECK</u>

Maximum insolation = IA_1 = 750 x 100 x 100 = 7.5 MW

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

$= \frac{1.18}{2} \times 90.2 \times (48.3)^3 = 6.0$ MW

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

= 1.18 x 100 x 100 x 0.4357 x 1005 x 0.2903

= 1.5 MW

This demonstrates the accuracy of the calculation and confirms the overall efficiency of 80%.

If we consider construction of this modular unit, the solar collector is of glass and of modest height and straightforward to build. The solar absorber has been described earlier and could be of height up to 1 metre.

The convergent nozzle should be of hyperbolic shape with the diameter of the mouth 3-4 times that of the throat to allow smooth acceleration of incoming air. If built of solid material, the nozzle will account for about 15% of the area of the solar collector. Since the turbine is of high efficiency it is considered that the nozzle does not need a divergent section.

The turbine required is of diameter 10.7 m, axle height about 5 m and maximum power 6 MW to harness the kinetic energy of air flow at up to 48.3 ms^{-1} (108 mph). Conventional wind turbines are designed for velocities of up to 15 ms^{-1}. Thus for this modular unit, a new turbine would need to be designed and built to harness the much higher power density.

The modular unit proposed has a solar absorber area of 100 x 100 m and a maximum output of 6.0 MW. If built in a tropical climate with annualised average daily insolation of 6 kWh per m^2 the mean output is 2 MW averaged over 24 hour/day and 365 days/year.

It is envisaged that modular units could be built virtually adjacent to each other on desert/scrub/ low value agricultural land. Thus a solar farm based on repeat units of the 100 x 100 m unit above would have an average output of about 160 MW/km^2.

Further comments

- Energy storage can easily be added reducing daytime peak production and allowing evening/night generation. Water storage tubes of up to one metre height can be placed on the ground underneath the solar absorber [6] taking up heat daytime from incoming ambient air and releasing this at night.

- Dust problems are minimised as incoming air is drawn from the atmosphere 15 metres above ground level.

- There is no water demand other than for periodic washing. This could be a major advantage over other solar thermal technologies.

Conclusion

A new configuration is described for harnessing solar energy using natural convection. It has similarities to the solar chimney but uses the entire solar collector area for a warm air store of modest height. This generates buoyancy drawing ambient air through the entire configuration at low velocity. All incoming air is required to flow through a central convergent nozzle where it is accelerated to high velocity. A turbine placed in the throat of the nozzle intercepts this flow kinetic energy and exports electricity. The only major energy loss is through exit air leaving the configuration at an elevated temperature. This heat loss is unavoidable – it is the buoyancy of the warm air store that drives the system – but it can be reduced by judicious choice of dimensions.

Theoretical development of the above model shows that an infinite number of variations are possible with an efficiency from 1 to 80%. For high efficiency, a substantial height is needed but the critical factors are the dimensions of, and the velocity of air flow through, the throat of the nozzle.

A modular unit is considered of solar collector area 100 x 100 m and warm air store height 10 m designed to achieve 80% efficiency. It requires a throat of nozzle and turbine diameter of 10.7 m to harness air flow velocity of up to 48.3 ms^{-1} (108 mph) at insolation 750 wm^{-2}. This would give a maximum output of 6 MW. If built in a tropical climate this modular unit would give an average output of 2 MW averaged over 24 hour/day and 365 days/year. If built in repeat patterns in a desert or on low value land, the modular units suggested would give an average output of about 160 MW/km^2.

The author asks individuals working in relevant disciplines to conduct further investigations into the above model using computational flow dynamics and other theoretical approaches; to build a laboratory model, a field-scale model and ultimately the large scale modular unit described to assess its feasibility and develop the proposal. The ideas involved are low tech and should be low cost and environmentally benign.

References

[1] J Schlaich, The Solar Chimney – Electricity from the Sun, Edition Axel Menges, Stuttgart, Germany, 1995.

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[4] A Koonsrisuk and T Chitsomboon, Energy, 51 (2013), 400-406.

[5] L B Mullett, International Journal of Ambient Energy, 8 (1987), 35-40.

[6] J Schlaich et al., Journal of Solar Energy Engineering, 127 (2005), 117-124.

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