Modular Units for Solar Electricity Large Scale using Natural Convection

Summary

A configuration is suggested where a large area solar collector provides a flow of warm air into and through a large volume warm air store. The height and elevated temperature of the latter creates a buoyancy force which draws ambient air through the configuration. Incoming air is required to flow through a convergent-divergent nozzle where a turbine is placed in the throat of the nozzle. By narrowing the throat of the nozzle, the kinetic energy of the air flow through the turbine can represent a large proportion of the solar energy absorbed. A solar module is described with a 200 x 200m solar collector devised to harness solar energy with 50% overall efficiency that would generate up to 15 Megawatts electricity at maximum insolation. Such units could be built on desert/scrub land at a density of 15-20 per km^2. The ideas are theoretical only. No experimental work has been conducted.

Introduction

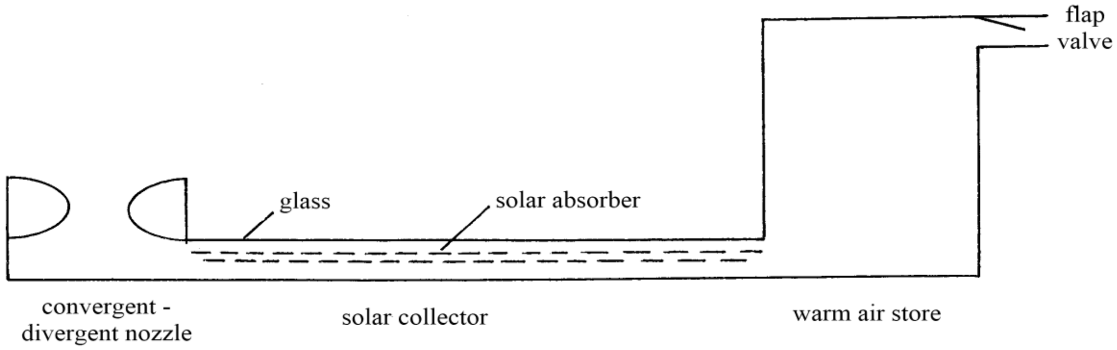

Figure 1

Consider the configuration shown in Figure 1. The central feature is a solar air collector of length and breadth 10-1000m. This absorbs solar energy with high efficiency heating air which rises into the warm air store which is of length, breadth and height 10-100m. This has two functions. The first is simply to allow transit of air flow into the atmosphere, with flap valves if necessary to prevent back flow. The second is to create a buoyancy force that draws fresh air through the entire configuration. Incoming air passes through a convergent-divergent nozzle (venturi) where the air flow must accelerate and decelerate as it is drawn through the nozzle.

During the day, solar energy is taken up by the absorber which warms air in its immediate vicinity. The warm air is lighter and flows into the warm air store. A convection current is established which takes warm air into and through the warm air store, drawing in replacement ambient air through the nozzle.

At constant insolation, a steady state is established where the air in the warm air store will be at a constant elevated temperature. This excess temperature compared to ambient air and the height of the warm air store generate a buoyancy force which draws air through the configuration. All the solar energy absorbed is taken away by this flow of warm air through the exit of the warm air store.

Consider now the convergent-divergent nozzle (venturi). As incoming air flows through the throat of the nozzle it must flow faster to travel through the constriction. The flow kinetic energy of the incoming air is multiplied as it approaches the constriction. Where does this flow kinetic energy come from? It comes from the internal energy (enthalpy) of the incoming air. Its molecules have to redistribute their energy to provide the extra linear flow velocity – but its temperature falls as a consequence as it flows through the constriction.

Immediately post-constriction, as the nozzle widens, the air flow must reduce velocity. The kinetic energy of its molecules is redistributed by turbulence and the temperature is restored to ambient as it enters the solar collector. There is no nett loss of energy by its flow through the nozzle.

Now consider what would happen if an air/wind turbine is placed in the throat of the nozzle. The turbine blades will rotate in the air flow. Some of the flow kinetic energy can be harnessed and exported as electricity. It will however cause a fall in temperature to below ambient for air entering the solar collector.

Consider now reducing the diameter of the throat of the nozzle. The flow velocity through the constriction is greater, the amount of electricity generated by the turbine is increased and there is a larger fall in temperature for air entering the solar collector.

It is the author's belief that as the constriction is steadily narrowed, a large fraction of the energy absorbed in the solar collector can be converted into electricity by the turbine.

A large amount of energy is lost via the warm air store but this is vital to create the buoyancy that drives the air flow. But conversion of solar energy into electricity should be possible with an efficiency of 10-20-50% and perhaps up to 80%.

Theoretical Development

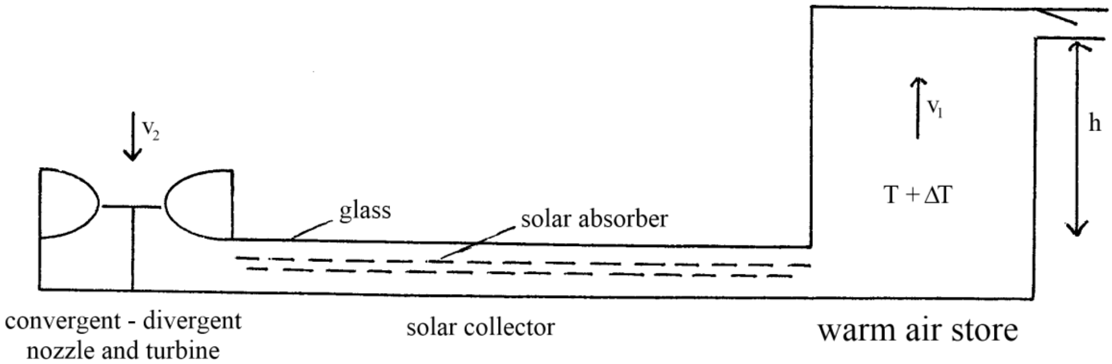

Figure 2

Consider the configuration shown in Figure 2 with symbols defined as follows:

T	ambient temperature
g	gravitational constant
C_p	heat capacity of air at constant pressure and temperature T
ρ	density of air at temperature T
I	insolation
A_1	cross-sectional area of warm air store
A_2	cross-sectional area of throat of nozzle
A_3	area of solar absorber
v_1	velocity of air flow through warm air store
v_2	velocity of air flow through throat of nozzle
h	height of warm air store
ΔT	excess temperature (above ambient) of air in warm air store
$\Delta T'$	fall in temperature (below ambient) of air entering solar collector

The warm air store of height h and cross-sectional area A_1 contains air at a temperature $T + \Delta T$. The buoyancy of this warm air column creates an air-flow velocity v_1 [1, 2] where

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

Consider the convergent-divergent nozzle. The cross-sectional area of the throat of the nozzle is A_2 and air flow velocity through the throat of the nozzle v_2. Constant mass flow requires that

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

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

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

As incoming air is drawn through the nozzle it is accelerated from rest to velocity v_2. The gain in flow kinetic energy causes a fall in temperature $\Delta T'$.

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

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

where m is the mass flow ($m = \rho A_1 v_1$)

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

It is considered that this flow kinetic energy is absorbed by the turbine with high efficiency and is exported as electricity. The air flow then enters the solar collector at a temperature $T - \Delta T'$.

Consider next the solar collector of area A_3 where the amount of solar energy absorbed is I per unit area. The total solar energy absorbed warms the air flow from an incoming temperature $T - \Delta T'$ to a leaving temperature of $T + \Delta T$.

total solar energy absorbed = mass flow x heat capacity x temperature rise

$$I\,A_3 = \rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T') \qquad (4)$$

If we consider collectively equations (1) to (4) the values of T g C_p ρ and I are all known. It leaves the variables A_1 A_2 A_3 v_1 v_2 h ΔT and $\Delta T'$. There are 4 equations and 8 variables. If four of these variables are fixed, the other 4 can be calculated. In this way an infinite number of possible dimensions can be considered and assessed for possible construction.

Solar Module

Consider the configuration shown in Figure 2 with the following dimensions

A_3	200 x 200m	T	300°	K
h	50m	g	9.81	ms^{-2}
ΔT	1.0°C	C_p	1005	$j\,kg^{-1}\,K^{-1}$
$\Delta T'$	1.0°C	ρ	1.18	$kg\,m^{-3}$
		I	750	$w\,m^{-2}$

The value for insolation I = 750 represents maximum UK summer insolation. By suggesting that $\Delta T = \Delta T'$ the module is being designed for an overall efficiency of 50%.

From equation (1) $\quad v_1^{\,2} = 2 \times \frac{1}{300} \times 9.81 \times 50$

$$v_1 = 1.8083\ ms^{-1}$$

From equation (3) $\quad v_2^{\,2} = 2 \times 1005 \times 1$

$$v_2 = 44.83\ ms^{-1}$$

From equation (4) $\quad A_1 = \dfrac{750 \times 200 \times 200}{1.18 \times 1.8083 \times 1005 \times 2}$

$$A_1 = 6995\ m^2$$

From equation (2) $\quad A_2 = \dfrac{6995 \times 1.8083}{44.83}$

$$A_2 = 282.1\ m^2$$

The above calculation shows that the warm air store required is of area $6995 m^2$ (83.6 x 83.6m). This represents 17.5% of the area of the solar collector. The area calculated for the throat of the nozzle $282.1 m^2$ would require a turbine of diameter 19.0m. The maximum velocity of air flow through the turbine is $44.83 ms^{-1}$ (100 mph). To build the solar module proposed would require the design and construction of a nozzle throat diameter 19.0m, mouth diameter about 100m. It also requires design and construction of a turbine of diameter 19.0m to harness the kinetic energy of airflow up to $44.83 ms^{-1}$.

Calculation Check

At maximum insolation total energy absorbed $= I A_3$

$= 750 \times 200 \times 200$

$=$ 30 Megawatts

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

$= \frac{1.18}{2} \times 282.1 \times (44.83)^3$

$=$ 15 MW

Energy lost through warm air store $=$ mass flow x heat capacity x temperature gain

$= \rho A_1 v_1 C_p \Delta T$

$= 1.18 \times 6995 \times 1.8083 \times 1005 \times 1$

$=$ 15 MW

The check confirms the 50% overall efficiency designed for the module. An approximate scale diagram of the solar module proposed is presented in Figure 3.

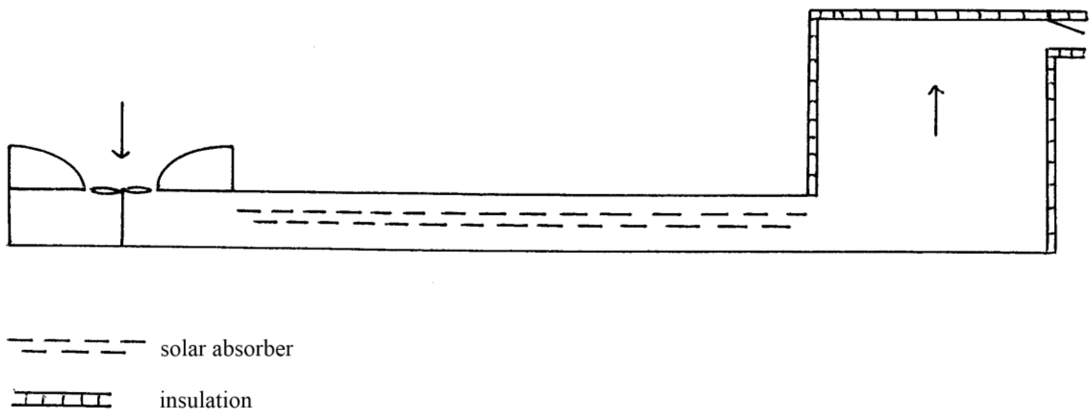

Figure 3

Further Comments

- If the air turbine has high efficiency, the divergent section of the nozzle could be much shorter or may be unnecessary.

- As air enters the solar collector at (T – 1) and leaves at (T + 1) there should be virtually no energy loss through the glass of the solar collector.

- It is suggested that the solar absorber should be multi layered and have a very open structure to allow free air flow. Efficient energy storage could be added in the absorber/collector area to reduce daytime peak production and allow evening/night generation.

- The configuration proposed has strong similarities to the solar chimney. The solar collector has the same function and has large area. The chimney is replaced by a warm air store of relatively larger area but much lower height. The low value of air flow velocity in the warm air store is then substantially multiplied pre turbine by the convergent nozzle; the amount of flow kinetic energy made available to the turbine is massively multiplied by the nozzle.

- The total land area taken up by the nozzle, turbine and warm air store represents about 40% of the area of the solar collector.

- The module proposed could be built in repeat units on desert/scrub land at a density of 15-20 modules per km^2.

- The entire structure of the solar module is low tech and should be low cost. Solar collector technology is well established. The warm air store is simply a large volume insulated rectangular/cubic structure. The nozzle and turbine would need to be specially designed and made but economies of scale would apply if there were many repeat units.

- Dust – incoming air for the solar module is drawn from the atmosphere from a height of about 20 metres. This should generally mean a very low level of airborne dust.

- Water – there is no water requirement. This could be a major advantage over other solar thermal power technologies in arid/desert climates.

References

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

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