SOLAR CONVECTION ENGINES

Summary

A new method is described for the conversion of solar energy into electricity. It involves natural convection using a solar air collector, a warm air store, a convergent-divergent nozzle and an air turbine. The collector has a large area and absorbs incident solar energy with high efficiency. This produces a flow of warm air which rises into and through a warm air store. This is of large volume and considerable height creating a strong buoyancy force which draws air into and through the solar collector with significant velocity. Incoming air passes through a convergent-divergent nozzle (venturi) before entering the solar collector. As air flows from the mouth to the throat of the nozzle the constriction demands a multiplication of its velocity. If a turbine is now placed in the throat of the nozzle it can harness the kinetic energy of the high velocity air flow producing electricity.

The warm air store of large dimensions provides a strong buoyancy force which draws ambient air through the configuration with significant velocity. The venturi multiplies this air flow velocity. As the cross-sectional area of the throat of the nozzle is reduced, the available kinetic energy increases continually. It is the author's belief that in the limiting case of a very narrow throat of nozzle, the kinetic energy of the air flow at this location can equal the total solar energy taken up by the absorber. A turbine can harness and export this energy – in this way solar energy can be converted into electricity with high efficiency.

Where does the kinetic energy of the incoming air come from? It is the warm air store that drives the system by providing a strong buoyancy force which draws incoming air through the nozzle and collector. As ambient air flows from the mouth to the throat of the nozzle, the constriction requires a multiplication of its linear velocity. The fast moving molecules that make up ambient air rearrange their motions to provide the flow kinetic energy but it is at the expense of their internal energy and so the temperature must fall. If there is no turbine, the temperature of ambient air is restored in the divergent section of the nozzle when the linear kinetic energy is dissipated. If a turbine is inserted it can export a large proportion of this flow kinetic energy as electricity. The temperature of the incoming air is then partly restored by the divergent section of the nozzle and then fully restored and raised by the solar absorber.

It is the author's belief that the use of optimum dimensions in the above arrangement will allow the conversion of solar energy into electricity with exceptionally high efficiency. Various configurations have been devised that illustrate possible applications e.g. garden solar electricity for an individual household, large scale generation using modular units on desert or scrub land in sunny regions, a 1000 MW solar power station using a man made mountain hollow or a mountain slope in a sunny climate. There is some attempt at cost estimates. Valuing electricity at $0.10/kWh and assuming 50% overall efficiency, these indicate a capital cost repayment period of about 3 years in sunny regions. If the principles are correct, then a miniaturised configuration may also be possible to provide solar home systems for individual households in rural developing countries.

This paper is purely theoretical – no experimental work has been conducted to validate or inform the proposals. The author asks individuals and organisations involved in solar/ renewable energy research or more widely in climate change/world energy supply to consider carefully the principles outlined, to initiate detailed investigation and to develop solar convection engines. This is the answer to the world energy problem.

Introduction

Consider a short tower of height h made of glass or transparent polymer with an efficient solar absorber inside the tower and just above its open base (Figure 1).

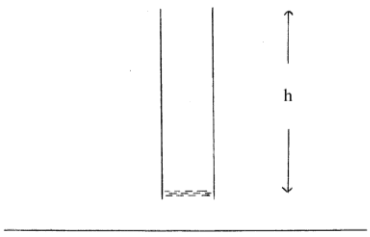


Figure 1

The solar absorber is metallic, abundantly perforated and multi-layered allowing free flow of air from beneath and rapid heat transfer; its upper surface is coated with solar absorber paint. It should be possible to construct such an absorber that will take up over 90% of incident solar energy, transfer the heat rapidly to neighbouring air molecules and allow easy flow of air through the absorber.

As solar energy is taken up by the absorber it warms neighbouring air which rises because of its lower density. Over a period, natural convection will establish a flow of air through the tower where

$$v^2 = 2\frac{\Delta T}{T} g h$$

v	velocity of air flow through tower
T	ambient temperature
ΔT	excess temperature air above absorber inside tower
g	gravitational constant
h	height of tower

Now consider adding, beneath the above arrangement, a constriction to the air flow in the form of a convergent-divergent nozzle or venturi (Figure 2).

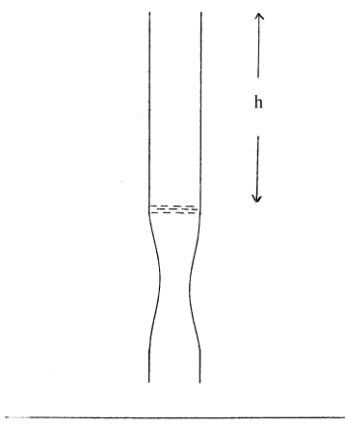


Figure 2

The height of the tower above the solar absorber remains as h; insolation is the same as previously and the temperature of the air above the solar absorber is again $T + \Delta T$. Thus the velocity of the air through the tower remains as previously.

But the velocity of the air flow through the constriction will be greater. Consider that

A_1	area cross-section of tower
A_2	area cross-section at throat of nozzle
v_1	velocity air flow through tower
v_2	velocity air flow through throat of nozzle

Constant mass flow requires that

$$A_1 v_1 = A_2 v_2$$

The kinetic energy of air flow at any level in the above extended tower is given by

$$\tfrac{1}{2} \text{ x mass flow x (velocity)}^2$$

Since the mass flow is constant then

$$\text{kinetic energy of air flow in throat of nozzle} = \left(\frac{A_1}{A_2}\right)^2 \text{ x kinetic energy of air flow through tower}$$

If a turbine was now placed in the throat of the nozzle it should be possible to harness many times the kinetic energy available in air flow through the tower itself.

But where does this extra kinetic energy come from? It must come from the internal energy of ambient air entering the base of the column. Ambient air is made up of a vast number of tiny molecules moving randomly in all directions with a root mean square velocity of about 450 m/s. As solar energy is taken up by the absorber and warms the air above, the latter exerts a buoyancy force drawing ambient air into the base of the column. This flows upwards with a velocity v_1. But as it encounters the constriction a much higher vertical velocity is needed. Through their random collisions with each other and with the walls of the container, the air molecules redistribute their internal energy to provide the higher vertical velocity. But it is at the expense of its internal energy and so its temperature falls as it approaches the throat of the nozzle.

In the divergent section above the throat of the nozzle in Figure 2 the vertical velocity falls back from v_2 to v_1. The slowdown restores the internal energy of ambient air to its previous value and the temperature rises back to ambient as it approaches the absorber.

Thus the temporary gain in kinetic energy and fall in temperature caused by the constriction is reversible with 100% efficiency. The phenomenon of kinetic energy apparently appearing out of nowhere is truly caused by the buoyancy of the air column above the absorber. It is a kind of positive feedback mechanism that solar energy taken up the absorber "creates" kinetic energy in air flow through the throat of the nozzle.

It is the author's belief that if a turbine was placed in the throat of the nozzle it has available an amount of kinetic energy $(A_1/A_2)^2$ times as much as is available to a turbine placed simply in the main flow through the tower.

Further, that in the limiting case, with a sufficiently narrow constriction, it should be possible for the kinetic energy of the airflow in the throat of the nozzle to be equivalent to the amount of solar energy taken up by the absorber.

Solar Convection Tower Engine

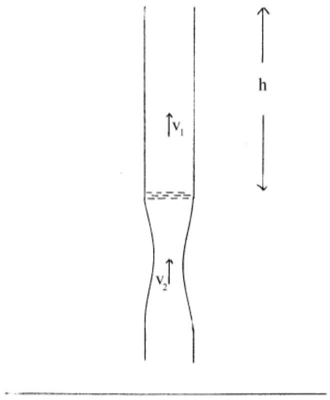


Figure 3

As previously consider a transparent tower of height h above a multilayered perforated solar absorber. Beneath the absorber is a venturi (convergent-divergent nozzle) with an open base to allow incoming air (Figure 3).

A_1	area cross-section of tower
A_2	area cross-section at throat of nozzle
v_1	velocity air flow through tower
v_2	velocity air flow through throat of nozzle
T	ambient temperature
ΔT	excess temperature air above absorber inside tower
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

For air flow through the tower

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

Constant mass flow requires

$$v_1A_1 \;=\; v_2A_2 \qquad (2)$$

Now consider the limiting case where the constriction is sufficiently narrow so that the kinetic energy of the air flow through the throat of the nozzle is equivalent to the total amount of solar energy taken up by the absorber

$$\tfrac{1}{2}\,\rho\,A_2\,v_2^{\,3} \;=\; I\,A_1 \qquad (3)$$

Also at this point the gain in kinetic energy for ambient air as it flows into the throat of the nozzle exactly equals the heat flow through the tower.

$$\tfrac{1}{2}\,v_2^{\,2} \;=\; C_p\,\Delta T \qquad (4)$$

From (1) and (4) eliminate ΔT

$$\frac{v_1^{\,2}\,T}{2\,g\,h} \;=\; \frac{v_2^{\,2}}{2C_p}$$

$$h \;=\; \left(\frac{v_1}{v_2}\right)^2 \frac{TC_p}{g}$$

From (2) $h = \left(\frac{A_2}{A_1}\right)^2 \frac{TC_p}{g}$

Consider $T = 300K \quad C_p = 1005$ J/kg. K $\quad g = 9.81$ m/s^2

$$h = \frac{300 \times 1005}{9.81} \left(\frac{A_2}{A_1}\right)^2$$

$$= 30{,}734 \left(\frac{A_2}{A_1}\right)^2$$

From this equation we can derive the following table

A_1/A_2	h (m)
1	30,734
10	307.34
50	12.3
100	3.07
200	0.77

This would suggest that with an A_1/A_2 ratio of 100 the height of the tower needed is just 3.07 metres to achieve 100% conversion of solar energy absorbed into flow kinetic energy in the throat of the nozzle. It is then simply a matter of intercepting this air flow with a turbine sited in the throat of the nozzle. But the turbine will take energy out of the system which will need to be compensated by using a greater tower height. It the turbine has 50% efficiency the author believes h will need to be doubled.

(Note that wind turbines in the open air are subject to the Betz efficiency limit of 16/27 or 59%. But for a ducted turbine efficiency can be over 80%. In that case the tower would need to be of height 5h. For the remainder of this paper, however, an overall efficiency of 50% will be assumed and a tower height required of 2h).

Solar Convection Tower Engine – Demonstration Model

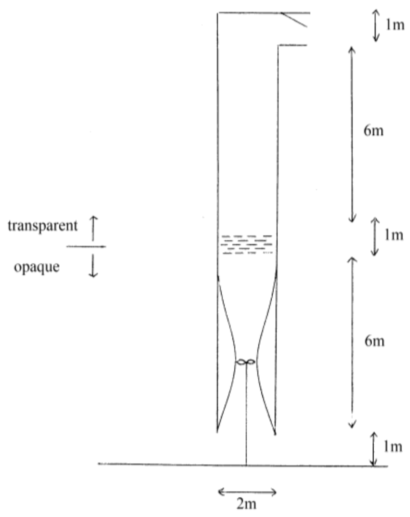


Figure 4

To illustrate the above principles it is suggested that a demonstration model could be built of dimensions as in Figure 4. The tower is of diameter 2 metres and the model has overall height 15m. It is based on $A_1/A_2 = 100$ and $h = 3.07$m. The throat of nozzle diameter is 0.2m giving a turbine of this diameter and axle height 4m. If we assume 50% overall efficiency it requires a height of 6m above the absorber. A similar height will be needed for the convergent-divergent nozzle. The tower above the absorber could be of glass, perspex or transparent polymer. Below the absorber it could be opaque. The nozzle and its support will need to be built of strong materials e.g. steel to withstand the high acceleration and deceleration of air flow through the nozzle.

Consider equations (1) to (4) previously where

$$T = 300\text{K} \quad C_p = 1005 \text{ J/kg.K} \quad g = 9.81 \text{ m/s}^2 \text{ and } \rho = 1.18 \text{ kg/m}^3$$

Consider $I = 750$ watts/m^2 which is maximum UK summer insolation.

Then in equation (3)

$$\tfrac{1}{2} \rho A_2 v_2^{\ 3} = I A_1$$

$$v_2^3 = \frac{2 \text{ x } 750 \text{ x } 100}{1.18} = 127{,}119$$

$$v_2 = 50.28 \text{ m/s} \quad (112 \text{ mph})$$

From equation (2) $\quad v_1 = 0.50$ m/s

From equation (4) $\quad \Delta T = \dfrac{50.28 \text{ x } 50.28}{2 \text{ x } 1005} = 1.26°\text{C}$

In the above calculation it is remarkable that such a small temperature rise for the warmed air in the tower can create such high air flow velocity through the throat of the nozzle. But this would be the result of complete conversion of solar energy absorbed into the maximum inflow kinetic energy in the throat of the nozzle. The very low temperature rise also emphasises the importance of rapid and efficient heat transfer from the solar absorber to the air flow. It is suggested that there be several layers of perforated absorber, perhaps as a metallic honeycomb with the upper surface only coated with solar absorber paint.

In the demonstration model the area of the solar absorber is 3.14 m^2. If overall efficiency is 50% it would have maximum output of 3.14 x 0.5 x 750 watts = 1.18 kilowatts.

The model described above would be instructive for theoretical reasons and could give useful experimental results to validate or otherwise the broad principles outlined in this paper. But it suffers the major practical disadvantage of requiring the solar absorber to be placed at a substantial height above the ground. In an earlier paper on this website (May 2008) the author has described the buoyancy driven solar engine shown in Figure 5.

<u>Buoyancy Driven Solar Engine</u> (BDSE)

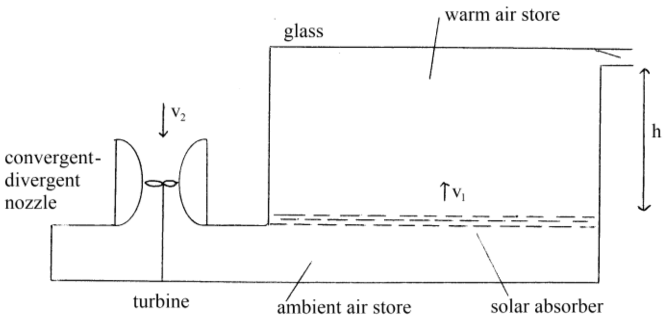


Figure 5

The convergent-divergent nozzle for incoming air and the turbine are sited laterally from the solar absorber and warm air store. Underneath and connecting both sections is the ambient air store.

Solar energy passes through the glass or transparent polymer of the warm air store. It is taken up with high efficiency by the solar absorber which is again multi layered and well perforated to allow smooth air flow and efficient heat transfer.

Insolation raises the temperature of air in the warm air store whose buoyancy then draws air through the configuration. Incoming air passes through a convergent-divergent nozzle where it is accelerated to high velocity through the throat of the nozzle. The nozzle would need to be built of strong material e.g. steel to withstand the very high acceleration and deceleration of air flow through the nozzle.

If the cross-sectional area of the solar absorber/warm air store and the throat of the solar nozzle and the height of the warm air store are optimised, it is possible for the kinetic energy of the air flow through the throat of the nozzle to be equivalent to the total solar energy taken up by the absorber. If a turbine is now placed in the throat of the nozzle this flow kinetic energy can be converted into electricity. Several applications will now be described of the above model.

<u>Garden Solar Electricity</u>

In Figure 5 consider that

A_1	area cross-section of warm air store
A_2	area cross-section at throat of nozzle
v_1	velocity air flow through warm air store
v_2	velocity air flow through throat of nozzle
h	height of warm air store
T	ambient temperature
ΔT	excess temperature of air inside warm air store
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

As previously, it is the warm air store that provides buoyancy drawing ambient air through the configuration. Its velocity v_1 through the warm air store is given by

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

Constant mass flow through the configuration requires that

$$v_1A_1 \ = \ v_2A_2 \qquad (2)$$

At optimum dimensions the area of cross-section of the throat of the nozzle is such that the kinetic energy of air flow through the throat of the nozzle exactly equals the amount of solar energy taken up by the absorber

$$\tfrac{1}{2}\,\rho\,A_2\,v_2^{\ 3} \ = \ I\,A_1 \qquad (3)$$

Also at this point the kinetic energy gain for ambient air as it flows into the throat of the nozzle exactly equals heat flow through the warm air store

$$\tfrac{1}{2}\,v_2^{\ 2} \ = \ C_p\,\Delta T \qquad (4)$$

From (1) and (4) eliminate ΔT

$$\frac{v_1^{\ 2}\,T}{2\,g\,h} \ = \ \frac{v_2^{\ 2}}{2C_p}$$

$$\left(\frac{v_2}{v_1}\right)^2 \ = \ \frac{TC_p}{g\,h}$$

From (2) $$\left(\frac{A_1}{A_2}\right)^2 \ = \ \frac{TC_p}{g\,h} \qquad (5)$$

For garden solar electricity we could consider a warm air store of length and breadth 5m and height 1 metre. Consider also

$T \ = \ 300K \quad C_p \ = \ 1005$ J/kg.K and $g \ = \ 9.81\ m/s^2$

$$\left(\frac{A_1}{A_2}\right)^2 \ = \ \frac{300 \times 1005}{9.81 \times 1} \ = \ 30{,}734$$

$$\frac{A_1}{A_2} \ = \ 175.3$$

but since $A_1 \ = \ 5 \times 5 \ = \ 25$ $\qquad A_2 \ = \ \frac{25}{175.3} \ = \ 0.1426\ m^2$

Consider the throat of the nozzle to have radius r then $\pi\,r^2 \ = \ 0.1426$ giving $r \ = \ 0.213m$ and diameter throat of nozzle = 0.426m.

In the above calculation we have considered h = 1 metre for 100% conversion solar energy into flow kinetic energy at the throat of the nozzle. If a turbine is now inserted of 50% efficiency then to provide the same buoyancy as above the height needed for the warm air store is 2 metres. Thus the final dimensions could be as in Figure 6.

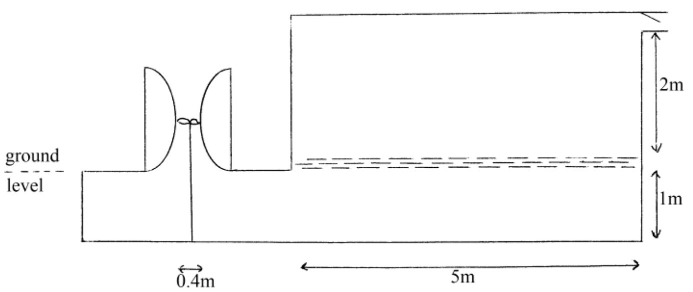


Figure 6

The ambient air store could be built below ground level. The solar absorber/warm air store would be built in the direction facing the sun. Consider equation (3)

ρ = density of air = 1.18 kg/m^3 A_1/A_2 = 175.3

Consider I = 750 watts/m^2 which is UK maximum summer insolation

$$v_2^{\,3} = \frac{2 \text{ x } 750 \text{ x } 175.3}{1.18} = 222{,}852$$

$$v_2 = 60.6 \text{ m/s (136 mph)}$$

From equation (2) v_1 = 0.35 m/s

From equation (4) ΔT = 1.83°C

The turbine would need to be of axle height 1.7m, diameter of blades 0.426m and harness air flow of up to 60.6 m/s (136 mph). Let us now consider the output and its value.

In the sunnier regions of the world there is average annualised insolation of 6 kWh/m^2/day. For the above configuration with solar absorber area 25m^2, assuming 50% overall efficiency there would be an average daily output of 75 kWh. Valued at $0.1/kWh this would provide electricity worth $7.50/day or $2700/year. The challenge would be to build/manufacture and install the above assembly for $10,000 to give a repayment period of 3-4 years.

Large scale Buoyancy Driven Solar Engine

Consider a model as in Figure 5 where the solar absorber and warm air store have an area 100m x 100m and the warm air store has height 10 metres. From equation (5) earlier

$$\left(\frac{A_1}{A_2}\right)^2 = \frac{TC_p}{g\,h}$$

$$= \frac{300 \text{ x } 1005}{9.81 \text{ x } 10} = 3073.4$$

$$\frac{A_1}{A_2} = 55.4$$

Since A_1 = 100 x 100 $A_2 = \frac{100 \text{ x } 100}{55.4}$ = 180.4m^2

If the throat of the nozzle has radius r then πr^2 = 180.4 hence r = 7.58m. Thus the throat of the nozzle has diameter 15.2m.

From equation (3) when I = 750

$$IA_1 = \tfrac{1}{2}\rho\, A_2\, v_2^{\,3}$$

$$v_2^{\,3} = \frac{2 \text{ x } 750 \text{ x } 55.4}{1.18} = 70{,}472$$

$$v_2 = 41.3 \text{ m/s (92 mph)}$$

From (2) v_1 = 0.75 m/s

From (4) ΔT = 0.85°C

In the above calculation the height of the warm air store h = 10m was used to give optimum dimensions for complete conversion of solar energy absorbed into flow kinetic energy in the throat of the nozzle with no turbine present. If a turbine is now installed of overall efficiency 50% the height of the warm air store will need to be doubled to 20m to provide the same buoyancy. The dimensions for a large scale BDSE model could be as in Figure 7.

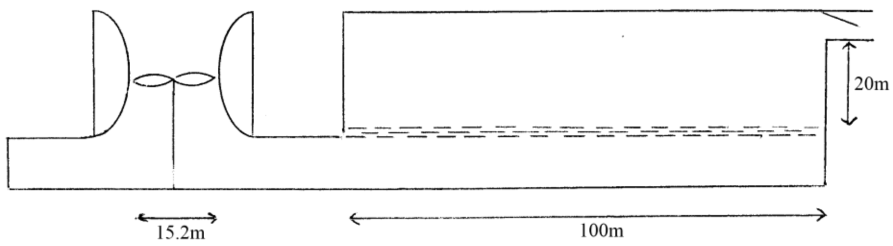


Figure 7

In sunny regions of the world average annualised insolation is 6 kWh/m^2/day. If the above 100m x 100m solar collector produced electricity with 50% overall efficiency it would mean daily output of 30,000 kWh. If we value this electricity at \$0.10/kWh then the value of the electricity produced is \$3000/day or \$1 million/year.

If we estimate the cost of the nozzle and turbine as \$2 million and the absorber/warm air store at \$1 million it would give a repayment period of 3 years.

The average output from the above module is 1250 kilowatts averaged over 24 hour/day and 365 days/year. If built in sequence in the deserts of China/India/USA/Sahara each square kilometre could accommodate 50 units giving a generation capacity of 60 Megawatts per square kilometre.

Hillside Solar Electricity

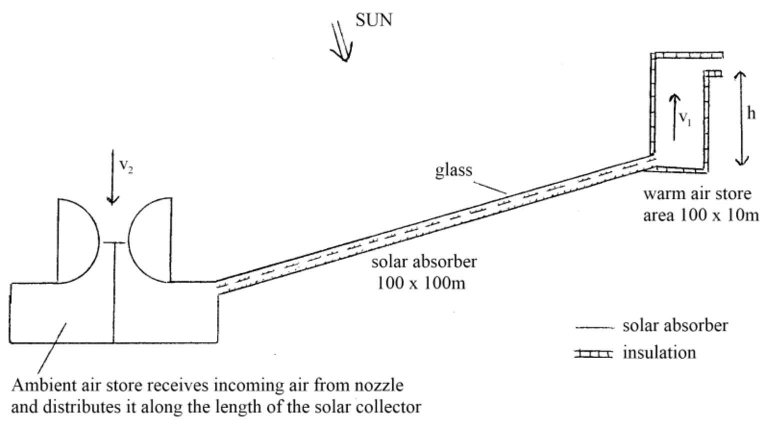


Figure 8

The solar absorber and warm air store are split in this configuration (Figure 8) to take advantage of improved insolation on an inclined plane. The solar collector can be several times the area of the warm air store; the absorber is again of loose structure, multilayered and metallic to allow easy air flow and rapid heat transfer. The solar collector is of glass or transparent polymer surface and could be double glazed perhaps of a glass/aerogel/glass sandwich to minimise heat losses. The warm air store is of concrete or cheap structural material but is well-insulated.

Consider

A_1	area warm air store
A_2	cross-sectional area throat of nozzle
A_3	area 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
T	ambient temperature
ΔT	excess temperature of air in warm air store
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

The buoyancy of the warm air store draws ambient air through the entire configuration whose velocity v_1 in the warm air store is determined by

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

Constant mass flow through the configuration requires that

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

At optimum dimensions the kinetic energy of air flow through the throat of the nozzle exactly equals the total solar energy taken up by the absorber

$$\tfrac{1}{2}\,\rho\,A_2\,v_2^{\,3} = I\,A_3 \qquad (3)$$

Also at these optimum dimensions the kinetic energy gained by ambient air flowing into the throat of the nozzle is equal to the heat flow through the warm air store

$$\tfrac{1}{2}\,v_2^{\,2} = C_p\,\Delta T \qquad (4)$$

In the configuration described consider that

A_1 = 100 x 10m A_3 = 100 x 100m h = 10m

T = 300K I = 750 watts/m^2 ρ = 1.18 kg/m^3

g = 9.81 m/s^2 C_p = 1005 J/kg.K

From (1) and (4) eliminate ΔT

$$\frac{v_1^{\,2}\,T}{2\,g\,h} = \frac{v_2^{\,2}}{2C_p}$$

$$\left(\frac{v_2}{v_1}\right)^2 = \frac{TC_p}{g\,h} = \frac{300 \times 1005}{9.81 \times 10}$$

From (2) $$\frac{A_1}{A_2} = \frac{v_2}{v_1} = 55.4$$

Since A_1 = 100 x 10 = 1000 m^2 $A_2 = \frac{1000}{55.4} = 18.0$ m^2

Thus the optimum value for the area of the throat of the nozzle is 18.0 m^2 giving a diameter of 4.8m.

Consider equation (3)

$$v_2^3 \quad = \quad \frac{2 \times 750 \times 100 \times 100}{1.18 \times 18.0} \quad = \quad 706{,}215$$

$$v_2 \quad = \quad 89.0 \text{ m/s} \ \ (199 \text{ mph})$$

From equation (2) $v_1 = 1.6$ m/s

From equation (4) $\Delta T = 3.9°K$

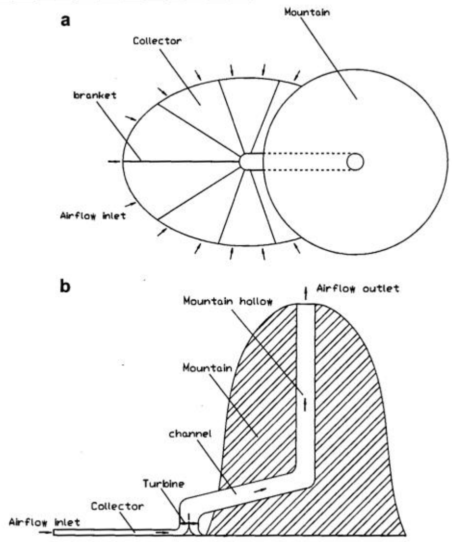
In the calculation above it has been assumed that h = 10m to give 100% conversion of solar energy into kinetic energy of air flow through the throat of the nozzle with no turbine present. If a turbine is now placed in the throat of the nozzle of 50% overall efficiency the height of the warm air store will need to be doubled to 20m.

The turbine above would have axle length about 20m and diameter 4.8m. The velocity of incoming air flow would be up to 89 m/s (200 mph). The nozzle and turbine would need to be built of very strong materials and would require rigid support.

The amount of electricity produced is as earlier with the large scale BDSE proposal and the economics would be comparable.

1000 MW Solar Power Station using a man made mountain hollow

Zhou, Yang, Wang and Xiao (Energy Conversion and Management, 50 (2009) 847-854) describe a novel concept for producing energy by integrating a solar collector with a mountain hollow (Figure 9).



Prototype of a novel concept for producing energy integrating a solar collector with a man made mountain hollow: (a) top view and (b) side view.

Figure 9

The principles come from the solar chimney but with the man made hollow easier to construct than a 1000m chimney whilst providing an identical draught/buoyancy force. The paper describes a solar collector of area 19.3 km^2 and a 1km elevation mountain hollow to provide 100 MW electricity. There is a detailed cost estimate with the conclusion that the energy cost in the long term is less than that of clean coal power plants.

Zhou et al. commend the suitability of their approach to countries with large areas of high mountains and a sunny climate. “For example, China, with a vast land area, is a mountainous country with two thirds of its total land area covered by mountains (33%), hills (10%) and plateaus (26%). Out of the world’s 12 highest peaks more than 8000m high, seven are located in China. In the western part of China, which contain most of China’s land, there is abundant sunlight, mostly more than 2000 hours per year, and is comprised of mountains and deserts as well as plateaus that do not provide much arable land for agriculture.”

The man made mountain hollow in the above concept has exactly the same role as the warm air store in this paper – it provides buoyancy and draws a draught of incoming air whose kinetic energy can be harnessed. In the paper by Zhou et al. the turbine is placed post collector pre mountain hollow. The present author prefers an arrangement where the turbine is placed pre collector. Also a convergent-divergent nozzle can multiply the velocity and available kinetic energy for the air flow. Consider the arrangement presented in Figure 10.

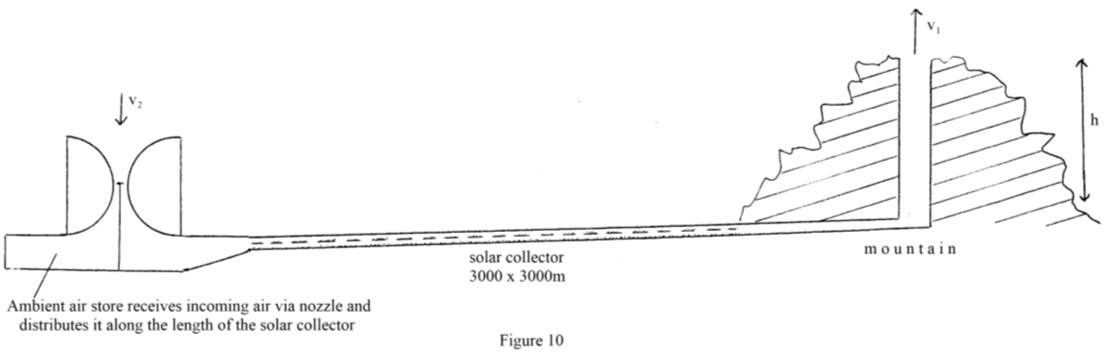


Figure 10

Consider that

A_1	cross-sectional area mountain hollow
A_2	cross-sectional area throat of nozzle
A_3	area solar absorber
v_1	velocity of air flow through mountain hollow
v_2	velocity of air flow through throat of nozzle
h	height of mountain hollow
T	ambient temperature
ΔT	excess temperature of air in mountain hollow
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

The buoyancy provided by warm air in the mountain hollow provides velocity v_1 where

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

Constant air flow through the configuration requires that

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

At optimum dimensions the kinetic energy of air flow through the throat of the nozzle exactly equals the solar energy taken up by the absorber

$$\tfrac{1}{2}\,\rho\, A_2\, v_2^{\,3} \;=\; I\, A_3 \qquad (3)$$

At this optimum point the kinetic energy gain for ambient air flowing into the throat of the nozzle exactly equals the heat flow through the mountain hollow

$$\tfrac{1}{2}\, v_2^{\,2} \;=\; C_p\, \Delta T \qquad (4)$$

In the configuration described consider that

$A_3 = 3000 \times 3000\text{m}$ $h = 500\text{m}$ $T = 300\text{K}$

$\Delta T = 10\text{K}$ $I = 750 \text{ watts/m}^2$ $\rho = 1.18 \text{ kg/m}^3$

$g = 9.81 \text{ m/s}^2$ $C_p = 1005 \text{ J/kg.K}$

From equation (4) $v_2^{\,2} = 2 \times 1005 \times 10$

$v_2 = 141.8 \text{ m/s}$ (317 mph)

From (1) $v_1^{\,2} = \dfrac{2 \times 10 \times 9.81 \times 500}{300}$

$v_1 = 18.08 \text{ m/s}$ (40.4 mph)

From (3) $A_2 = \dfrac{2 \times 750 \times 3000 \times 3000}{1.18 \times (141.8)^3}$

$A_2 = 4013 \text{ m}^2$

This gives diameter throat of nozzle 71.5m

From (2) $A_1 = \dfrac{141.8 \times 4013}{18.08} = 31{,}474 \text{ m}^2$

If the mountain hollow is of circular cross-section, it would require a diameter of 200m.

The height used in the above calculation $h = 500\text{m}$ is for complete conversion of solar energy into kinetic energy of air flow through the throat of the nozzle with no turbine present. If a turbine is now included that has an overall efficiency of 50% the value of h needs to be doubled to 1000m.

The cost of construction of such a solar power station can be estimated using some of the figures used by Zhou et al. p 853.

Excavation of mountain hollow		$31{,}474 \times 1000 \text{ m}^3$ at \$56.31 per m^3	\$1772 million
Collector cost	9 km^2		53
Nozzle and turbine			1000
		TOTAL	\$3000 million

The amount of electricity produced assuming average annualised insolation of 6 kWh/m^2/day and 50% overall efficiency with a collector area of 3000 x 3000m is 27×10^6 kWh/day. Note that this represents an average output of 1125 MW averaged over 24 hour/day and 365 days/year. If the electricity is valued at \$0.10/kWh it gives a total value of \$2.7 million/day or \$985 million/year. This would give a repayment period of 3 years.

1000 MW Mountain Slope Solar Power Station

In mountainous areas it should be possible to take advantage of steeply sloping terrain to provide the height needed for a warm air store. The solar collector could itself be built on the inclined land with the glass/transparent polymer surface built several metres from the ground to allow a large volume of warm air to provide buoyancy. See Figure 11.

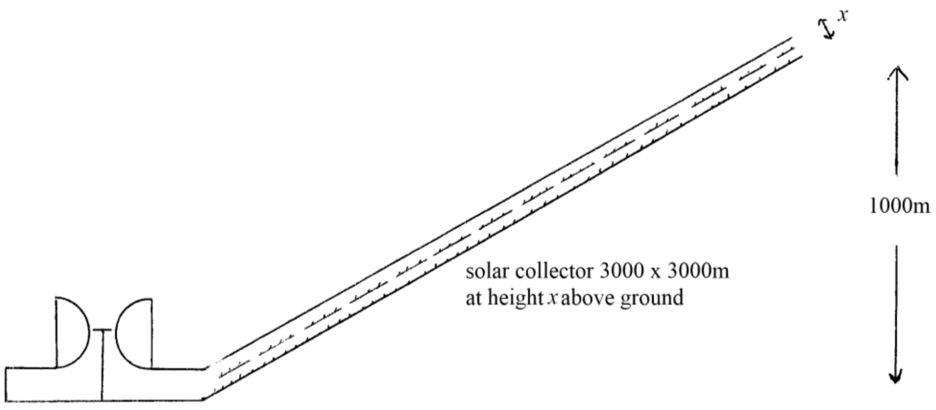


Figure 11

Consider a mountain slope of 30° engineered/levelled to provide a smooth surface for the construction of a solar collector 3000 x 3000m at a distance *x* from the ground. The vertical rise over the length of the solar collector is 1000m.

Consider that

A_1	cross-sectional area of the open mouth of the solar collector
A_2	cross-sectional area of the throat of the nozzle
A_3	area of solar collector
v_1	velocity of air flow through the solar collector
v_2	velocity of air flow through the throat of the nozzle
h	height of top of collector above base
T	ambient temperature
ΔT	excess temperature of warm air leaving the solar collector
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

Consider

$A_1 = 3000\,x$	$A_3 = 3000 \times 3000\text{m}$	$h = 500\text{m}$
$T = 300\text{K}$	$\Delta T = 10\text{K}$	$I = 750 \text{ watts/m}^2$
$\rho = 1.18 \text{ kg/m}^3$	$g = 9.81 \text{ m/s}^2$	$C_p = 1005 \text{ J/kg.K}$

The buoyancy of warm air in the solar collector draws incoming air through the solar collector with a velocity v_1 where

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

But the average temperature of air in the solar collector will only be 5°C above ambient. Thus

$$v_1^{\,2} \quad = \quad \frac{2 \times 5 \times 9.81 \times 500}{300}$$

$$v_1 \quad = \quad 12.79 \text{ m/s} \ \ (28.6 \text{ mph})$$

Constant mass flow through the configuration requires that

$$v_2 A_2 \quad = \quad 3000\, x\, v_1 \qquad (2)$$

At optimum dimensions the kinetic energy of air flow through the throat of the nozzle exactly equals the total solar energy taken up by the absorber

$$\tfrac{1}{2}\rho A_2 v_2^{\,3} = I A_3 \qquad (3)$$

Also at optimum dimensions the kinetic energy gain for ambient air flowing into the throat of the nozzle exactly equals the heat flow through the system

$$\tfrac{1}{2} v_2^{\,2} \quad = \quad C_p \Delta T \qquad (4)$$

From (4) $\quad v_2^{\,2} \quad = \quad 2 \times 1005 \times 10$

$$v_2 \quad = \quad 141.8 \text{ m/s} \ \ (317 \text{ mph})$$

From (3) $\quad A_2 \quad = \quad \dfrac{2 \times 750 \times 3000 \times 3000}{1.18 \times (141.8)^3} \quad = \quad 4013 \text{ m}^2$

Thus the throat of the nozzle has diameter 71.5m

From equation (2) $\quad x \quad = \quad \dfrac{141.8 \times 4013}{3000 \times 12.79} \quad = \quad 14.8\text{m}$

Thus the transparent surface of the solar collector would need to be built 14.8 metres above the ground.

In the calculation a value $h = 500$m was used for the vertical height gain in the solar collector. This gives the optimum dimensions for 100% conversion of the solar energy absorbed into flow kinetic energy in the throat of the nozzle with no turbine present. If a turbine is now installed of overall efficiency 50% the vertical height must be doubled to 1000m as in Figure 11.

The turbine required above would have axle height about 50m, blade diameter 71.5m and deal with air flow at up to 141.8 m/s (317 mph).

Comparing this proposal to the earlier man made mountain hollow, the cost of the solar collector will be several times greater but the cost of geo engineering a mountain slope of 3000 x 3000m to provide a smooth surface should be much less than the cost of excavation of a mountain hollow.

Cost of preparation of smooth surface for solar collector and erection of collector/warm air store		$1000 million
Nozzle and turbine		1000 million
	TOTAL	$2000 million

The amount of electricity produced would be as earlier – an average of 1125 MW averaged over 24 hour/day and 365 days/year. Valued at $0.10/kWh the electricity would have a total value of $985 million/year giving a repayment period of 2 years.

Solar Convection Engine with Side Air Entry

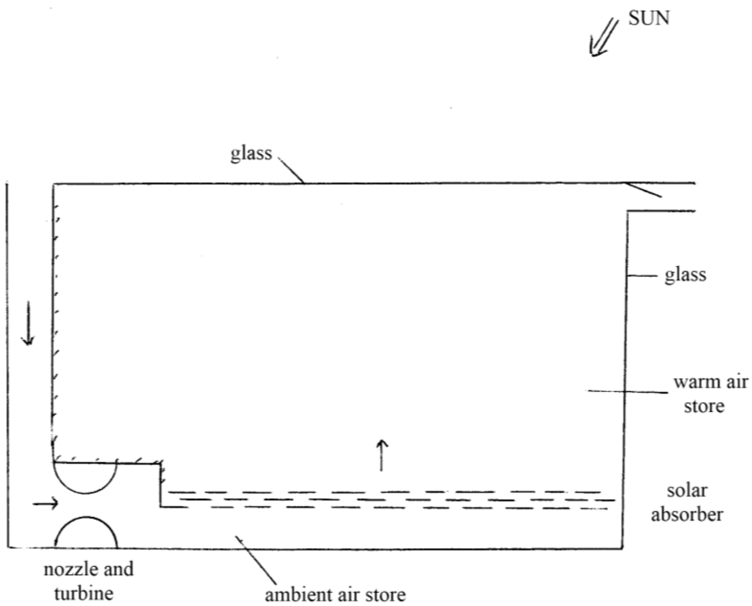


Figure 12

Solar convection engines could be developed with side air entry as in Figure 12. It could allow vertical air intake to reduce any dust problems. The turbine has a horizontal axis and feeds incoming air to an ambient air store. The latter feeds the solar absorber from ground level. The nozzle containment and the vertical side facing the sun could also be coated with solar absorber paint. The above configuration maximises the volume of the warm air store.

Solar Convection Engine with Central Nozzle and Warm Air Store Surround

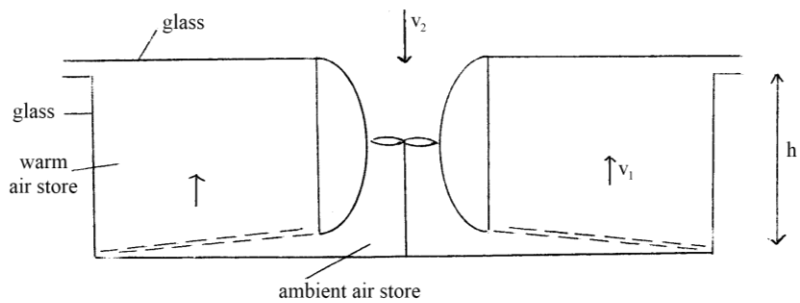


Figure 13

The convergent-divergent nozzle is the central feature of this configuration (Figure 13). Solar energy is taken up by the absorber warming air in its vicinity which rises. This draws replacement ambient air which is accelerated to high velocity through the nozzle. A turbine placed at the throat of the nozzle can harness this energy. Consider that

A_1	area solar absorber
A_2	cross-sectional area of throat of nozzle
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
T	ambient temperature
ΔT	excess temperature of warm air store
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

The velocity of air flow through the warm air store is given by

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

Constant air flow through the configuration requires that

$$v_1A_1 = v_2A_2 \qquad (2)$$

With optimum dimensions the kinetic energy of the air flow through the throat of the nozzle exactly equals the amount of solar energy taken up by the absorber

$$\tfrac{1}{2}\,\rho\,A_2\,v_2^{\,3} = I\,A_1 \qquad (3)$$

Also under these optimum conditions the gain in kinetic energy by ambient air as it flows into the throat of the nozzle exactly equals the heat energy flow through the warm air store

$$\tfrac{1}{2}\,v_2^{\,2} = C_p\,\Delta T \qquad (4)$$

Now consider a configuration where

diameter warm air store	=	30m
diameter nozzle and housing	=	10m

Also consider

$h = 5\text{m}$ $\qquad T = 300\text{K}$ $\qquad I = 750 \text{ watts/m}^2$

$\rho = 1.18 \text{ kg/m}^3$ $\qquad g = 9.81 \text{ m/s}^2$ $\qquad C_p = 1005 \text{ J/kg.K}$

$$\text{area solar absorber} = \pi R^2 - \pi r^2$$

$$= 3.14\,(225 - 25)$$

$$A_1 = 628 \text{ m}^2$$

From (1) and (4) eliminate ΔT

$$\frac{v_1^2\ T}{2\,g\,h} = \frac{v_2^2}{2C_p}$$

$$\left(\frac{v_2}{v_1}\right)^2 = \frac{TC_p}{g\,h} = \frac{300 \times 1005}{9.81 \times 5} = 6146.8$$

From (2) $\frac{A_1}{A_2} = \frac{v_2}{v_1} = 78.4$

$$A_2 = \frac{628}{78.4} = 8.01 \text{ m}^2$$

This give a diameter throat of nozzle 3.19m.

From (3) $v_2^3 = \frac{2 \times 750 \times 78.4}{1.18} = 99{,}663$

$$v_2 = 46.4 \text{ m/s (104 mph)}$$

From (2) $v_1 = 0.59$

From (4) $\Delta T = 1.07°K$

In the above calculation it is assumed that h = 5m for air flow with no turbine present. If a turbine is now installed in the throat of the nozzle of 50% overall efficiency the height of the warm air store will need to be doubled to 10m.

The turbine required would have axle height 5 metres and blade diameter 3.19m. It would have to deal with air flow velocity of up to 46.4 m/s (104 mph).

The above configuration is included in this paper because it is radically different to earlier arrangements. It demonstrates the overwhelming importance of the convergent-divergent nozzle which accelerates and then decelerates incoming air. It would need to be built of strong materials e.g. steel, carbon fibre and housed in a robust structure. All of these materials for the central section can be opaque. In the example described the solar absorber forms the outer annulus but accounts for 90% of the area. Larger or smaller units could be devised following the principles above. It is the author's view that energy losses are minimized in this arrangement and efficiencies of up to 80% may be achievable.

The configuration as specified with solar absorber area 628 m^2, in a sunny climate with insolation 6 kWh/m^2/day and assuming 50% efficiency, would generate 1884 kWh/day. Valued at $0.10/kWh the electricity would be worth $188.4/day or $69,000/year. The author believes the economics would be as good or better than any of the other proposals in this paper.

If the above module of 30m diameter was built inside a 40m side square then there could be 625 units/km^2. The above unit generates an average of 78.5 kilowatts averaged over 24 hour/day and 365 days/year. Built in this way on desert land they would offer generating capacity of 50 MW/km^2.

Solar Home Systems

If the principles outlined in this paper are correct, then it should be possible to devise a miniaturised system for home electricity generation. There are over 1 billion people living in rural areas in developing countries with no access to electricity and whose lives could be transformed if such 'solar home systems' were available at an economic price. It is the author's belief that all of the configurations presented can be miniaturised but it would present a considerable challenge to produce such units at an economic price. Consider the configuration shown in Figure 14.

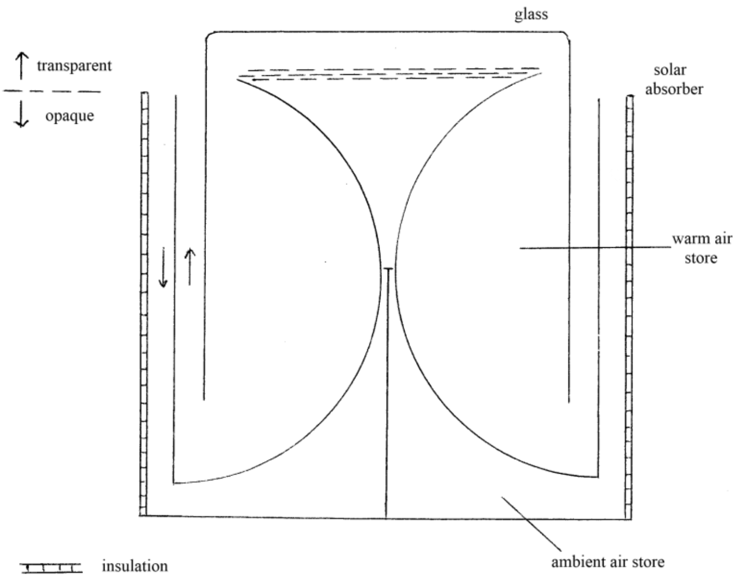


Figure 14

The solar absorber is sited at a high level underneath glass or transparent polymer. All the materials below this level can be opaque allowing the nozzle, turbine and containment to be made of strong materials. The solar absorber warms air in its neighbourhood which rises. Its only exit pathway is via the warm air store and into the exit vertical pipe. Convection draws ambient air via the down pipe into the ambient air store and then via the nozzle to the absorber. The warm air store provides buoyancy driving the system. Consider

A_1	area solar absorber
A_2	cross-sectional area throat of nozzle
v_1	velocity of air flow through solar absorber
v_2	velocity of air flow through throat of nozzle
h	height of warm air store
T	ambient temperature
ΔT	excess temperature of warm air store
I	insolation
ρ	density of air
g	gravitational constant
C_p	heat capacity of air

Consider that the entire structure is cylindrical with a solar absorber diameter of 2 metres. $A_1 = 3.14 \times 1 \times 1 = 3.14 \text{ m}^2$. Also consider

$h = 1\text{m}$	$T = 300\text{K}$	$I = 750 \text{ watts/m}^2$
$\rho = 1.18 \text{ kg/m}^3$	$g = 9.81 \text{ m/s}^2$	$C_p = 1005 \text{ J/kg.K}$

The velocity of air through the absorber and warm air store is usually given by

$$v_1^{\,2} = 2 \frac{\Delta T}{T} g h$$

This is for a cylindrical warm air store. In this case however about one half of the volume of the cylinder is lost to the convergent-divergent nozzle. This reduces the buoyancy force to one half. Thus

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

Constant air flow requires that

$$v_1A_1 \quad = \quad v_2A_2 \qquad (2)$$

At optimum dimensions the kinetic energy of air flow through the throat of the nozzle exactly equals the amount of solar energy absorbed

$$\tfrac{1}{2}\,\rho\, A_2\, v_2^{\,3} \quad = \quad I\, A_1 \qquad (3)$$

Also at those optimum dimensions the kinetic energy acquired by ambient air as it flows into the throat of the nozzle exactly equals the heat flow through the warm air store

$$\tfrac{1}{2}\, v_2^{\,2} \quad = \quad C_p\, \Delta T \qquad (4)$$

From (1) and (4) eliminate ΔT

$$\frac{v_1^2\ T}{g\ h} \quad = \quad \frac{v_2^2}{2C_p}$$

$$\left(\frac{v_2}{v_1}\right)^2 \quad = \quad \frac{2\,TC_p}{g\,h} \quad = \quad \frac{2 \times 300 \times 1005}{9.81 \times 1}$$

From (2) $\qquad \dfrac{A_1}{A_2} \quad = \quad \dfrac{v_2}{v_1} \quad = \quad 247.9$

Thus if $\quad A_1 = 3.14\ m^2 \quad A_2 = 0.0127\ m^2$

This gives the diameter of the throat of the nozzle as 0.127m. This is 12.7 cm.

From (3) $\qquad v_2^3 \quad = \quad \dfrac{2 \times 750 \times 247.9}{1.18} \quad = \quad 315{,}162$

$\qquad v_2 \quad = \quad 68.1$ m/s (152 mph)

From (2) $\qquad v_1 \quad = \quad 0.275$

From (4) $\qquad \Delta T \quad = \quad 2.31°C$

The above calculation has been carried out for complete conversion of solar energy into kinetic energy in the throat of the nozzle assuming h = 1m and assuming there is no turbine present. If a turbine is now installed of 50% overall efficiency the height of the warm air store will need to be doubled to 2m.

The turbine required above would be of axle height 1m, blade diameter 12.7 cm and deal with air flow up to 68.1 m/s (152 mph).

Assuming 50% efficiency its maximum output would be $\dfrac{3.14}{2} \times 750$ watts = 1.18 kW

The output of the model proposed, assuming 50% overall efficiency and a sunny climate with average annualised insolation of 6 kWh/m^2/day and 3.14 m^2 solar absorber area would be 9.42 kWh/day. If the electricity is valued at \$0.10/kWh the value of electricity generated is 365 x 0.942 = \$344 year.

The challenge would be whether the solar home system described above could be mass manufactured for \$1000 each to give a repayment period of 3 years.

Conclusion

The ideas outlined in this paper are based on theoretical work only. No experimental work has been carried out. The author asks individuals working in a university department, industrial company or energy research institute to consider carefully the principles involved and to undertake serious practical research work on buoyancy driven solar engines.

The proposals have some parallel with the solar chimney but a convergent-divergent nozzle (venturi) is used to multiply air flow velocity and hence available kinetic energy. Also the nozzle and turbine are placed before rather than after the solar collector to harness energy from INCOMING air flow.

Solar energy can be absorbed efficiently on a large scale in a solar air collector creating a flow of warm air which feeds a warm air store open to the atmosphere. The large volume of warm air provides a buoyancy force that draws ambient air into the solar collector. If this incoming air flow has to pass through a convergent-divergent nozzle its velocity is multiplied as it flows into the throat of the nozzle. In the limiting case the kinetic energy of air flow through this constriction can equal the amount of solar energy taken up by the collector. If there is no turbine, this flow kinetic energy is simply dissipated in turbulence as the air flows through the divergent part of the nozzle. If, however, a turbine is placed in the throat of the nozzle it can harness the flow kinetic energy with high efficiency.

The clever part of the proposal is that work is extracted from the air flow <u>before</u> it passes through the solar collector. The energy doesn't come from nowhere – it comes from the internal energy of ambient air whose molecular motions are rearranged as it approaches the constriction to provide vertical kinetic energy at the expense of its random kinetic energy and so its temperature will fall as it passes through the nozzle. This is buoyancy drawing air and doing work by a positive feedback mechanism. The author believes that by this arrangement it should be possible to convert solar energy into mechanical energy and then electricity with high efficiency.

The ideas described are low tech and should allow the generation of electricity from solar energy much more cheaply than from concentrated solar power (CSP) and at a small fraction of the cost from photovoltaics. The author suggests several configurations that could be built for test and development and possible application. The reader could devise other configurations/variations based on the same principles that may be more practical/economic. The units involved could be built on scrub land, desert or even mountainous areas in sunny countries ... but generally on land that has no agricultural value. There is no water requirement and most of the proposals have little or no environmental impact.

The author asks people who have expertise in solar technologies or more widely those involved in research work in renewable energy/physics/global warming to look carefully at the ideas presented, to investigate, assess, develop, build and market solar convection engines. This is the answer to the world energy problem.

Dr Alan Williams ***March 2011***