The Solar Nozzle – a possible approach for

Efficient, Large Scale, Solar Electricity

Summary

The author proposes a new method for conversion of solar energy into electricity using natural convection in an open cycle. A convergent nozzle made of glass or other transparent material is arranged vertically with a modest gap between the open base and ground level. A solar absorber abundantly perforated and several layers thick or of metallic honeycomb structure is arranged in the lower levels but above the base of the nozzle. The elaborate solar absorber structure is required to provide rapid heat transfer. Solar energy absorbed warms air in its neighbourhood which rises because of its buoyancy drawing in ambient air to replace. As the air flows through the nozzle it accelerates because of the narrowing/constriction. Heat energy acquired from the absorber is converted into the kinetic energy of flow. A wind turbine placed in the throat of the nozzle converts flow kinetic energy into electricity. A critical height is calculated for given nozzle dimensions where all of the solar energy absorbed is converted into kinetic energy. This could allow the conversion of solar energy into electricity with high efficiency. A prototype solar nozzle is proposed of base diameter 10 metres, throat diameter 1 metre, and height 10 metres. Calculation indicates that at maximum UK summer insolation this could give an electricity output of up to 59 kilowatts. Solar farms could be built of such modular units. Larger prototypes with capacity up to 5 Megawatts are described. An alternative configuration using incoming air into a nozzle pre solar absorber is also described which would be more compact and have higher power density. In all cases the systems proposed are driven simply by the buoyancy of warm air. All the proposals are theoretical and the author asks others to build, test, evaluate and develop the ideas.

Introduction – a brief outline of the Proposal

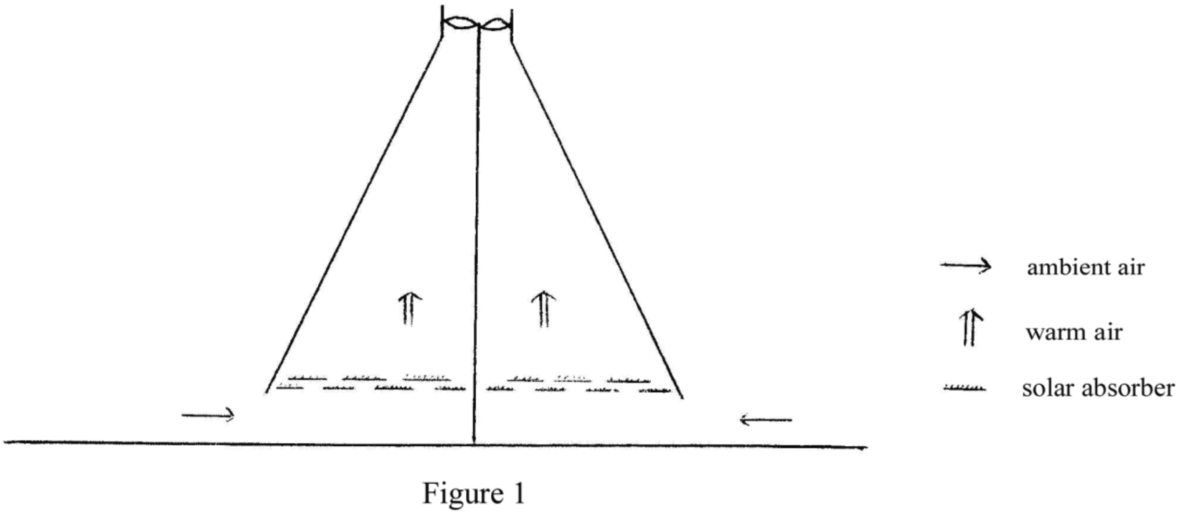

Figure 1

A convergent nozzle built of glass or other transparent material is arranged vertically (Figure 1). A gap is left between the base of the cone and the ground to allow access of air. An abundantly perforated solar absorber several layers thick or of honeycomb structure is placed in the lower levels above the base of the cone. This is designed to allow highly efficient heat transfer of solar energy absorbed to surrounding air. A horizontal rotation vertical axis wind turbine is sited in the throat of the nozzle.

Solar energy is taken up with high efficiency by the absorber. This warms air in its neighbourhood which rises because of its buoyancy drawing in ambient air to replace. As the warm air rises through the nozzle it gains velocity because of the constriction attaining its highest velocity in the throat of the nozzle. A wind turbine extracts this flow kinetic energy producing electricity.

It is the author’s belief that it is possible to devise suitable dimensions for the diameter of the absorber, the diameter of the throat of the nozzle and the height of the cone such that ALL of the solar energy taken up by the absorber is converted into the kinetic energy of air flow through the nozzle. It should thus be possible to convert solar energy into electricity with high efficiency.

The Solar Chimney

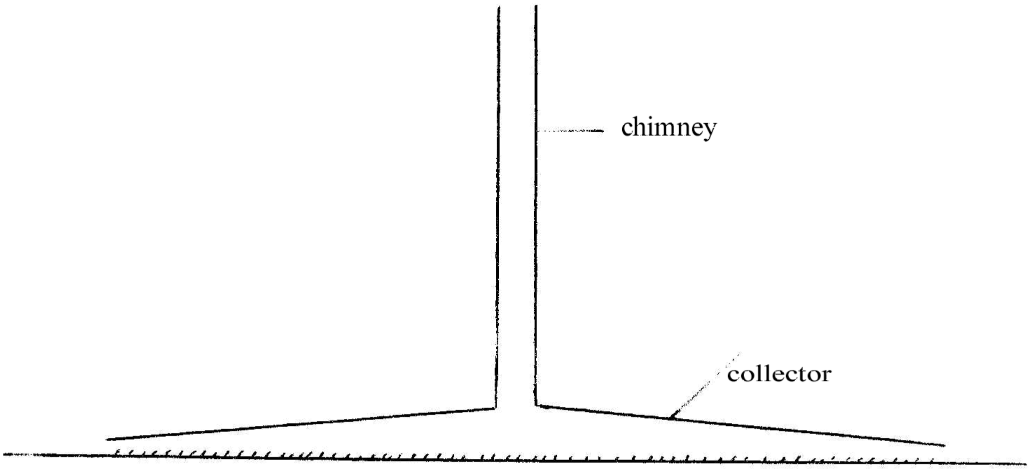

Figure 2

The principles of the solar chimney are elaborated in detail by Schlaich [1, 2]. The solar absorber is at ground level under a large area transparent solar collector (Figure 2). Warm air rises under the gently sloping collector and then through a very tall chimney. The overall pressure difference Δp driving the air flow is given by

$$\Delta p = \frac{\Delta T}{T} \rho g h$$

where T is the ambient temperature, ΔT is the temperature rise for air in the chimney, ρ the density of air, g the gravitational constant and h the height of the chimney.

Turbines are placed at the base of the chimney. Calculation gives for a 1000 metre chimney, an overall efficiency of conversion of solar energy into electricity of 2-3%.

Padki and Sherif [3] suggested a small model solar chimney of radically different geometry (Figure 3).

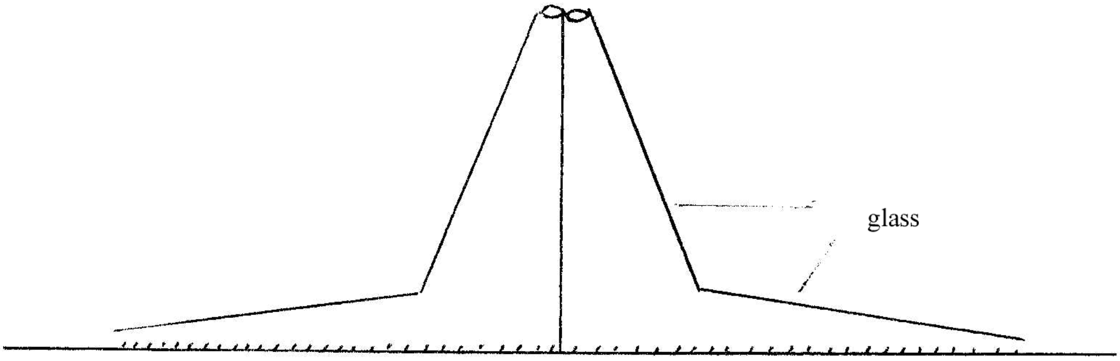

Figure 3

In this case the chimney is conical with the turbine placed at the narrowing of the cone. The velocity of the air climbing the chimney is multiplied by A_1/A_2 where A_1 is the area of the base of the chimney and A_2 the area swept by the turbine. The efficiency of the chimney is multiplied by $(A_1/A_2)^2$. The paper is mainly theoretical but the authors argue that "It would seem that there is no upper bound on the efficiency" quoting a graph with efficiency of up to 20% as the A_1/A_2 ratio is increased. Unfortunately the practical results reported are much less impressive.

Ninic [4] in a paper titled "Available Energy of the Air in Solar Chimneys and the possibility of its Ground Level Concentration" repeatedly points out that the thermal gain in the solar collector is far greater than that harnessed by the Schlaich solar chimney and argues that improved efficiency may be possible "by creating a special velocity field above the ground level plant."

Liu Wei et al. [5] in a theoretical model investigating air flow through the base of the chimney find that a constriction in the chimney accelerates the flow. "The result suggests that it is feasible to increase the power output by modifying the local configuration of the solar chimney power plant."

Coetzee [6] in a paper titled "Design of a Solar Chimney to Generate Electricity Employing a Convergent Nozzle" attaches a nozzle and turbine at the top of a 36 metre chimney and $1600m^2$ solar collector. In the theoretical model the diameter of the throat of the nozzle is one half that of the chimney. This increases the velocity of the air flow by a factor of 4 and its available energy by a factor of 16. In the Discussion section of the paper, Coetzee considers increasing the air velocity by a factor of 4-20 with consequent dramatic reduction in projected electricity costs!!

The above references indicate that it should be possible to harness far more energy than in the straightforward Schlaich cylindrical solar chimney and that this could be variously achieved by using a constriction/conical chimney/convergent nozzle. In each case above these are add-on modifications of the solar chimney.

In the current proposal, the author has completely redesigned the solar chimney. The different slopes of the collector and chimney are brought into one integral structure – that of a large convergent nozzle or conical chimney. The solar absorber is placed inside the base of the cone, rather than at ground level to allow highly efficient heat transfer to the air flow. The third critical difference is that the turbine is at the top of the chimney/nozzle where the velocity of the air flow is greatest.

The Solar Nozzle – Theoretical Background

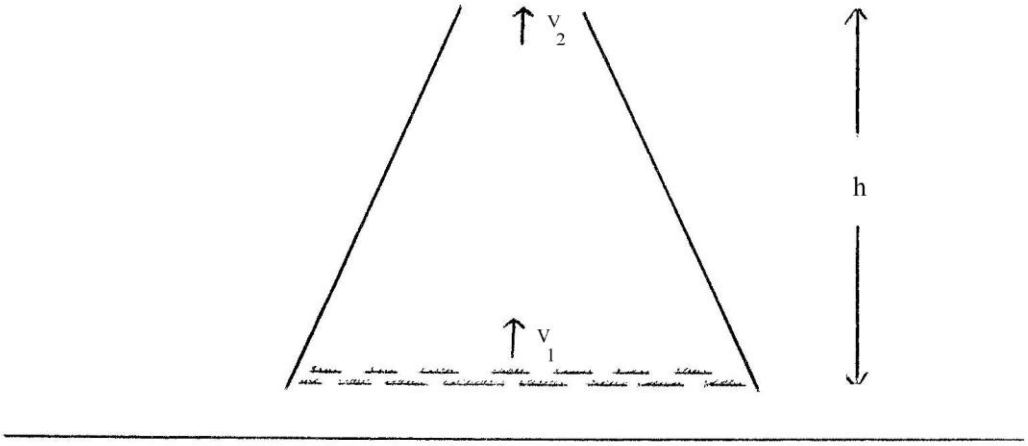

Figure 4

Consider a solar nozzle as depicted in Figure 4 of

height	h	metres
base of cone/solar absorber area	A_1	m^2
throat of nozzle area	A_2	m^2
velocity of air at solar absorber level	v_1	m/s
velocity of air in throat of nozzle	v_2	m/s
ambient temperature	T	ºK
temperature rise for air flow through absorber	ΔT	ºK

For the solar chimney the fall in pressure due to warm air in the chimney as quoted earlier

$$\Delta p = \frac{\Delta T}{T} \rho g h$$

In the solar nozzle we have a cone instead of a cylinder, the volume of air displaced is one third that of the solar chimney and

$$\Delta p = \frac{1}{3} \frac{\Delta T}{T} \rho g h$$

Δp also represents the dynamic pressure at solar absorber level.

Thus $$\Delta p = \frac{1}{2} \rho v_1^2 = \frac{1}{3} \frac{\Delta T}{T} \rho g h$$

from which $$v_1^2 = \frac{2}{3} \frac{\Delta T}{T} g h \qquad (1)$$

For the nozzle there is uniform mass flow

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

Consider that in the ideal theoretical configuration A_1, A_2 and h are such that ALL of the heat energy taken up by the absorber is transferred to the air flow and in its passage through the nozzle is converted into the kinetic energy of air flow in the throat of the nozzle.

Consider that insolation is I watts/m^2. The total amount of solar energy taken up by the absorber is then I A_1.

For air flow through the throat of the nozzle

$$\text{Kinetic energy} = \frac{1}{2} m v^2$$

$$= \frac{1}{2} \rho A_2 v_2 \ . \ v_2^2$$

If there is 100% conversion of solar energy absorbed into the kinetic energy of air flow then

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

The solar energy absorbed gives the air flow an average temperature rise ΔT. For unit mass of air the heat absorbed is $C_p \Delta T$ where C_p is the heat capacity in joules/kg.K. If this is entirely converted into kinetic energy at the throat of the nozzle

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

Equations (1) – (4) can be used to solve the physics of the solar nozzle.

From (1) and (4) eliminate ΔT

$$\frac{3 T v_1^2}{2 g h} = \frac{v_2^2}{2 C_p}$$

$$h = \frac{3 T C_p}{g} \left[\frac{v_1}{v_2} \right]^2$$

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

Thus $$h = \frac{3 T C_p}{g} \left[\frac{A_2}{A_1} \right]^2$$

This equation gives the critical height for 100% conversion of solar energy into kinetic energy for different A_2/A_1 ratios.

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

$$h = \frac{3 \times 300 \times 1005}{9.81} \left[\frac{A_2}{A_1} \right]^2$$

$$h = 92{,}202 \left[\frac{A_2}{A_1} \right]^2$$

From this equation, the following table is derived

A_1/A_2	h (metres)
1	92,202
4	5,763
10	922
30	102
60	25.6
100	9.22
200	2.31
500	0.37
1000	0.092

Table 1

Table 1 demonstrates that the higher is the ratio of A_1/A_2 i.e. the larger is the base of the cone/nozzle and the narrower is the throat, the lower is the critical height to achieve 100% conversion of solar energy absorbed into the kinetic energy of flow in the throat of the nozzle.

For $A_1/A_2 = 1$ the critical height is 92 km!! This is effectively the case for the solar chimney though it is exaggerated by a factor of 3 as the calculation is based on a cone whereas the solar chimney is a cylinder.

For A_1/A_2 ratios of 4-30 the critical height is inconveniently large, bearing in mind that the turbine needs to be sited at the top of the nozzle.

For A_1/A_2 ratios of 60-200 the critical height is conveniently manageable to devise a commercial version of the solar nozzle. An A_1/A_2 ratio of 100 and a critical height of 9.22 metres has been selected as the basis for an exemplary proposal in the remainder of this paper.

For A_1/A_2 ratios of 200-500, the critical height is 2.31 to 0.37 metre. This could be the basis of solar nozzles built for microgeneration or to provide solar home systems in rural areas in developing countries.

Prototype Solar Nozzle

Equations (1) to (4) can be used to give a detailed picture as to how a prototype solar nozzle might work. Assume ambient temperature T 300°K, $A_1/A_2 = 100$ and h = 9.22 m. Consider further insolation of 750 watts/m^2. This is the maximum for UK summer. The density of air ρ is 1.293 kg/m^3 at 0°C and atmospheric pressure. At 300°K the density of air is

$$\frac{273}{300} \times 1.293 = 1.17663$$

From equation (3)

$$v_2^3 = \frac{750 \times 100 \times 2}{1.17663}$$

$$= 127{,}483$$

$$v_2 = 50.32 \text{ m/s}$$

From equation (2)

$$v_1 = 0.5032 \text{ m/s}$$

From equation (4)

$$\Delta T = \frac{50.32 \times 50.32}{2 \times 1005}$$

$$\Delta T = 1.26^{\circ}\text{C}$$

Calculation indicates that at maximum UK summer insolation, assuming 100% conversion of solar energy absorbed into kinetic energy, the air flow through the throat of the nozzle has a velocity of 50.32 m/s (112 mph). This may sound quite startling – but these are the forces that produce hurricanes when heat energy from warm oceanic waters creates similar strong winds.

Note that the temperature rise due to the solar absorber is relatively very low at 1.26ºC. This underlines the importance of extremely efficient heat transfer from the solar absorber to the incoming air flow. The structure of the absorber could involve several well-perforated layers or a honeycomb metallic structure coated with absorber paint. It is vital that ΔT should be kept as low as possible – a solar absorber depth of up to one metre should be allowed with a fine structure that allows dozens of collisions for each molecule of air with absorber surface so that there is rapid and complete equilibration.

For flow through a convergent nozzle there is a loss of static pressure and an equivalent gain of dynamic pressure given by

$$\frac{1}{2}(v_2^2 - v_1^2) = \frac{\Delta p}{\rho}$$

$$\Delta p = [\,(50.32)^2 - (0.5032)^2\,] \times \frac{1.17663}{2}$$

$$\Delta p = 1490 \text{ Pascals}$$

The pressure to drive the flow is provided by buoyancy. As quoted earlier the buoyancy force for the solar chimney is given by

$$\Delta p = \frac{\Delta T}{T} \rho\, g\, h$$

In the case of the solar nozzle, a cone has one third of the volume of the chimney; in the prototype solar nozzle considered

$$\Delta p = \frac{1}{3} \times \frac{1.26}{300} \times 1.17663 \times 9.81 \times 9.22$$

$$= 0.1490 \text{ Pascals}$$

This is the dynamic pressure at solar absorber level. But as the air flow rises through the nozzle it accelerates so that $v_2 = 100\ v_1$. Since dynamic pressure is proportional to the square of velocity then in the throat of the nozzle

$$\Delta p = 0.1490 \times (100)^2$$

$$= 1490 \text{ Pascals as required above.}$$

The Nozzle - multiplies velocity of air flow by 100

- multiplies dynamic pressure by $(100)^2$
- multiplies available kinetic energy by $(100)^2$

Fluid Mechanics of Solar Nozzle Flow

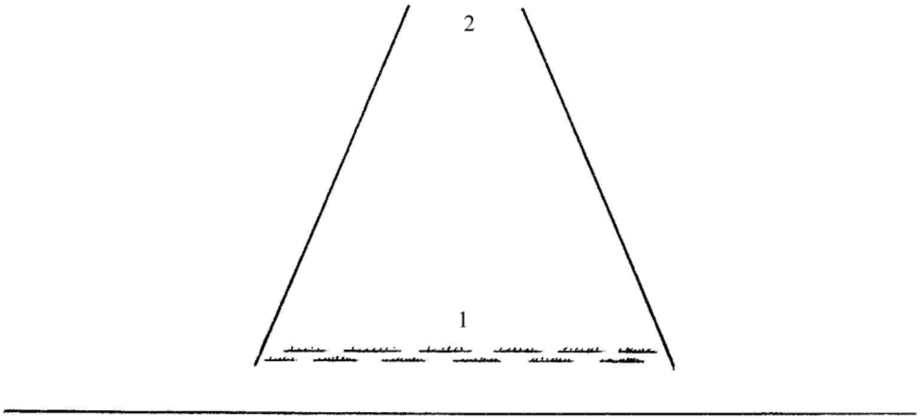

Figure 5

Consider that in Figure 5

	temperature	pressure	density
ambient air	T	P	ρ
site 1	T_1	P_1	ρ_1
site 2	T_2	P_2	ρ_2

For adiabatic flow through a convergent nozzle

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{(k-1)/k} = \left[\frac{\rho_2}{\rho_1}\right]^{(k-1)}$$

where k = 1.4

Bernoulli's principle requires that total pressure is constant throughout the flow. Thus

static pressure at (1) + dynamic pressure at (1) = static pressure at (2) + dynamic pressure at (2) = ambient pressure

$$P_1 + \frac{1}{2}\rho v_1^{\,2} = P_2 + \frac{1}{2}\rho v_2^{\,2} = P$$

The dynamic pressure at site (1) $= \frac{1}{2}\rho v_1^{\,2} = \frac{1.17663}{2} \times (0.5032)^2$

$= 0.1490$ Pascals

The dynamic pressure at site (2) $= \frac{1}{2}\rho v_2^{\,2} = \frac{1.17663}{2} \times (50.32)^2$

$= 1490$ Pascals

$P = 101{,}300$ Pascals

$P_1 = 101{,}300 - 0.1490$
$= 101{,}299.85$

$P_2 = 101{,}300 - 1490$
$= 99{,}810$

We can now double check whether the values calculated for T_1, T_2, P_1, P_2 conform to the equation quoted above

$$\frac{T_2}{T_1} = \frac{300}{301.26} = 0.9958176$$

$$\left[\frac{P_2}{P_1}\right]^{(k-1)/k} = \left[\frac{99{,}810}{101{,}299.85}\right]^{0.4/1.4} = [0.9852927]^{0.28571}$$

$$= 0.995774$$

The result is in almost exact agreement. The adiabatic flow equation can further be used to calculate the change in density as air flows through the nozzle

$$\left[\frac{\rho_2}{\rho_1}\right]^{(k-1)} = \left[\frac{P_2}{P_1}\right]^{(k-1)/k}$$

$$\log \frac{\rho_2}{\rho_1} = \frac{1}{1.4} \log \frac{99{,}810}{101{,}299.85}$$

$$\frac{\rho_2}{\rho_1} = 0.989472$$

Note that ρ_1 is about 1% larger than ρ_2. Thus there is a fall in density as air flows through the nozzle. The air above the solar absorber already has a density lower than ambient air, but flow through the nozzle will reinforce this buoyancy effect and may mean that a slightly lower nozzle height h is needed.

From the above calculation $\frac{\rho_1 - \rho_2}{\rho_1} = \frac{\Delta \rho}{\rho} = 0.010528$

Note also in the above results that

$$\frac{\Delta p}{P} : \frac{\Delta T}{T} : \frac{\Delta \rho}{\rho} = \frac{1490}{101{,}300} : \frac{1.26}{300} : 0.010528$$

$$= 0.014709 : 0.0042 : 0.010528$$

$$= 3.50 : 1 : 2.51$$

$$C_p : R : C_v$$

It is possible to double check the above results using the gas laws. Consider a fixed mass of gas moving from site 1 to site 2 in the nozzle (Figure 5). The gas laws require that

$$\frac{P\,V}{T} = \text{constant} = \frac{P}{T\rho}$$

$$\frac{P_1}{T_1\rho_1} = \frac{P_2}{T_2\rho_2}$$

$$\frac{\rho_2}{\rho_1} = \frac{P_2T_1}{P_1T_2} = \frac{99{,}810 \times 301.26}{101{,}300 \times 300} = 0.98943$$

This is in almost exact agreement with the value calculated earlier.

It is also possible to double check the internal consistency of the above calculations by calculating the power available to a turbine placed in the throat of the nozzle. The output achieved is proportional to the product of volume flow and the fall in pressure at the turbine. Consider that in the prototype solar nozzle the solar absorber has diameter 10 metres and the throat of the nozzle diameter 1 metre.

Maximum Insolation = $I\,A_1$

= $750 \times 3.14 \times 5 \times 5$

= 58.9 kilowatts

Power available at turbine = $\Delta p\ v_2\ A_2$

= $1490 \times 50.32 \times 3.14 \times 0.5 \times 0.5$

= 58.9 kilowatts

Dimensions of Solar Nozzle Prototype Suggested

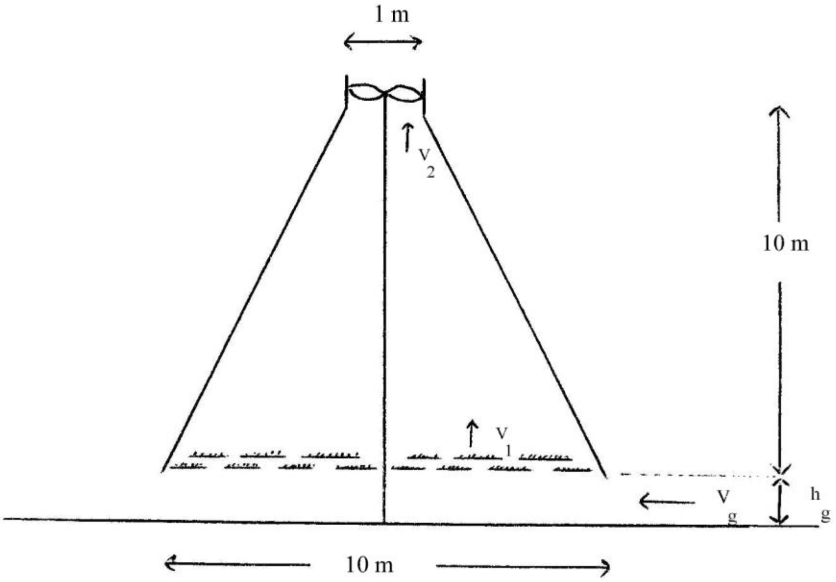

Figure 6

The central example considered in this paper (Figure 6) has

A_1/A_2 100 h 9.22m v_2 50.32 m/s v_1 0.5032 m/s
ΔT 1.26°C Δp 1490 Pa

Since the critical height is 9.22 metres it is suggested that the nozzle be of vertical height 10 metres to allow for a band of solar absorber layers or metallic honeycomb of up to 1 metre height.

The nozzle has base diameter 10 metres and throat diameter 1metre. If there was 100% efficiency then at insolation 750 watts/m^2 the velocity of air through the absorber is 0.5032 m/s and through the throat of the nozzle is 50.32 m/s.

A turbine is required of height 10 metres and diameter 1 metre able to deal with an air flow velocity of up to 50 m/s (112 mph) thus having a capacity of up to 59 kilowatts. Ducted turbines are not subject to the Betz limit and have an efficiency of about 80% [7].

Ground Velocity

Some consideration must be given to ambient air entering the base of the solar nozzle (Figure 6). Consider that the base of the nozzle is at height h_g above ground level and that ambient air entering the nozzle has a horizontal velocity v_g. If the base of the nozzle has radius r, then constant mass flow requires that

$$2 \pi r h_g v_g = \pi r^2 v_1$$

$$v_g = \frac{r v_1}{2 h_g}$$

In the prototype considered above r = 5 metres and $v_1 = 0.5$. Consider that $h_g = 1$ metre then

$$v_g = \frac{5 \times 0.5}{2 \times 1} = 1.25 \text{ m/s}$$

The ground velocity should present no problem at this level.

Larger Prototype

If the prototype solar nozzle described above gave successful results, larger units could be considered. Maintaining A_1/A_2 100 and height 10 metres, the absorber diameter could be increased to 20 to 100 metres increasing the turbine diameter in step as in Table 2

diameter solar absorber (m)	10	20	50	100
diameter turbine (m)	1	2	5	10
maximum insolation (kW)	59	236	1480	5900

Table 2

Ground air velocity could be a problem for very large units e.g. in the latter case r = 50, $v_1 = 0.50$ if $h_g = 1$ metre then ground velocity $v_g = \frac{50 \times 0.5}{2 \times 1} = 12.5$ m/s (28 mph)

If $h_g = 5$ metres then ground air velocity is reduced to a more reasonable maximum 2.5 m/s.

For units of large diameter perhaps it would be better to consider a lower A_1/A_2 ratio and greater height. From Table 1 an A_1/A_2 ratio of 60 has a critical height of 25.6 metres. Equation (3) earlier then gives

$$v_2^{\,3} = \frac{750 \times 60 \times 2}{1.17663} = 76{,}490$$

$$v_2 = 42.45 \text{ m/s}$$

If the solar absorber was of 100 metre diameter it would require a turbine of diameter $100 \div \sqrt{60} = 12.9$ metres. The dimensions would be as in Figure 7.

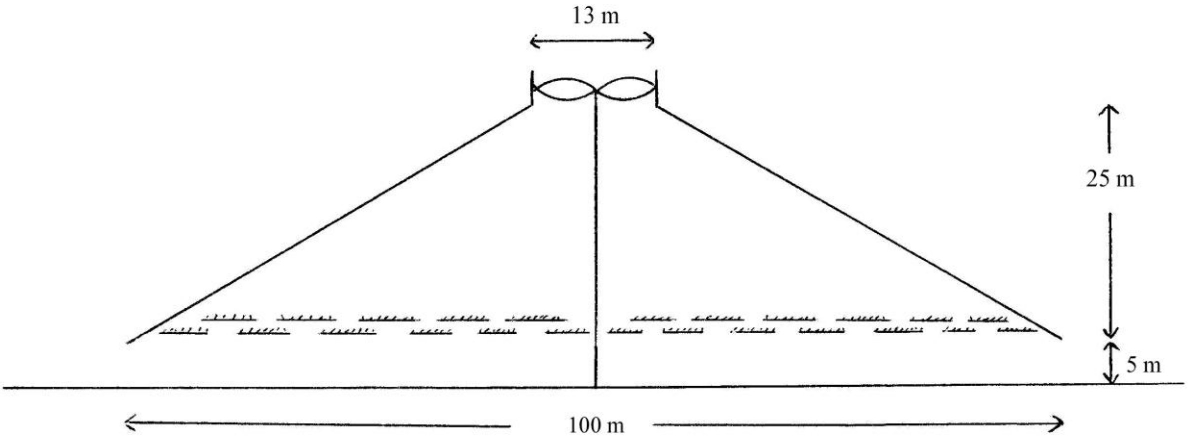

Figure 7

The larger prototype as described would have a solar collector diameter of 100 metres, a total height of about 30 metres and a turbine diameter of 13 metres. UK maximum summer insolation will generate an air velocity of up to 42.45 m/s (95 mph) and an output of up to 5.9 Megawatts.

In the tropics the average annual insolation is 6 kWh/m^2/day or an all the year round, day and night average of 250 watts/m^2. Thus the unit described would have an average output of up to 2 MW.

Solar Farm

The solar nozzle has no particular land requirement other than the area depicted above. But if it was proposed to build many modular units on one large site, the ground velocity described earlier could become a problem. This could be solved by building each nozzle inside a transparent shield (Figure 8) where downflow from the atmosphere could provide the air needed by the solar nozzle without creating side wind. Units as described could be relatively closely packed.

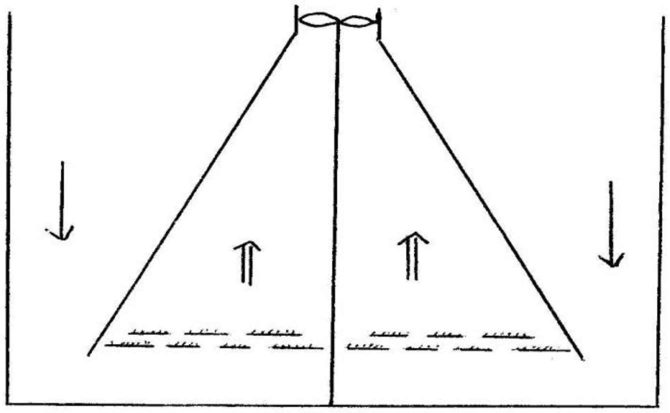

Figure 8

Solar Nozzle with Turbine using Incoming Air

The buoyancy force caused by warm air rising from the solar absorber into a chimney draws ambient air into the solar collector. The latter could pass through a convergent nozzle pre absorber. Incoming air flow is accelerated to high velocity and intercepted by a wind turbine placed in the throat of the nozzle. The arrangement is shown in Figure 9.

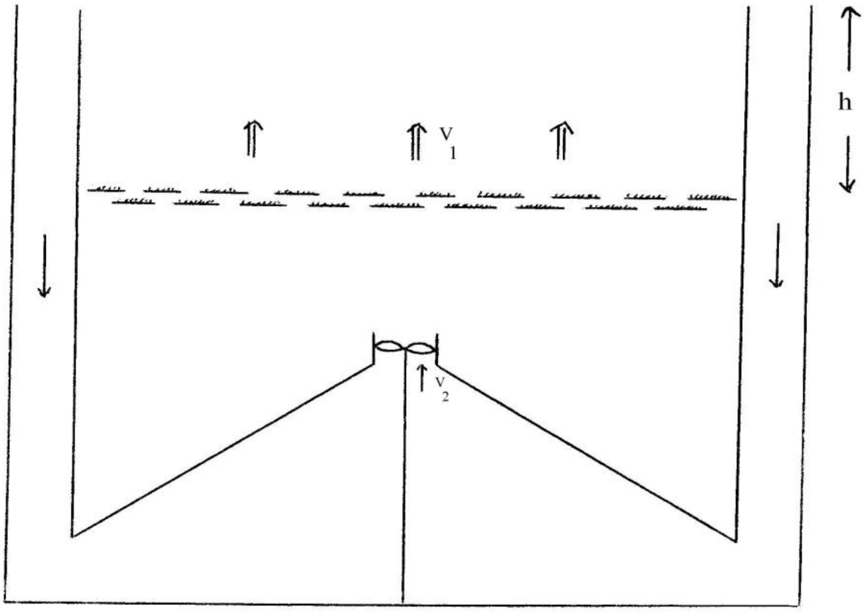

Figure 9

The physics is essentially as earlier with A_1 representing the solar absorber area, A_2 the area of the throat of the nozzle, v_1 the velocity of air flow at the solar absorber and v_2 the velocity of air flow in the throat of the nozzle. The critical height h now represents the height of the cylinder or chimney above the absorber. Since the volume of the cylinder is three times that of a cone, the critical height for this configuration will be one third those presented in Table 1.

There could be particular advantages for this configuration. All the structural materials above the level of the solar absorber must be transparent but other materials (NOT metals) could be used for all components beneath absorber level. This could allow for stronger materials for the nozzle and turbine, the use of higher A_1/A_2 ratios and a higher v_2. Since h is one third that previously the entire structure would be more compact.

A prototype to test the above ideas is outlined in Figure 10. With A_1/A_2 100, the critical height for the cylindrical chimney is 3.07 metres. As previously with absorber diameter 10 metres, turbine diameter 1 metre, at maximum insolation 750 watts/m^2 $v_2 = 50.32$ $v_1 = 0.50$ and $\Delta T = 1.26°C$. The amount of solar energy intercepted and maximum output is 59 kilowatts. As previously, much larger capacity solar nozzles could also be devised based on this configuration.

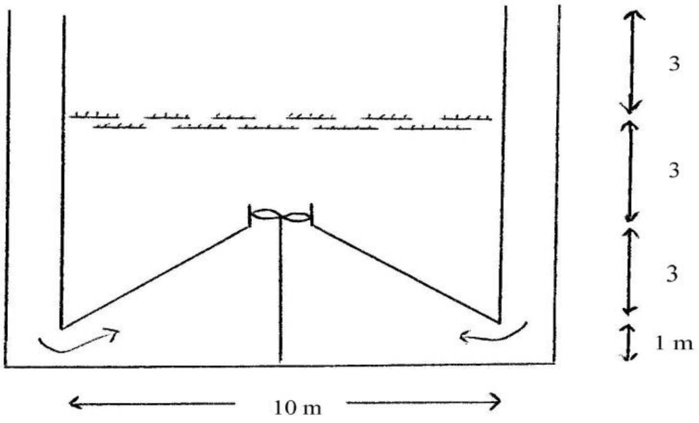

Figure 10

Convective Acceleration – “g” forces

When heat is converted completely into wind energy, a relatively small amount of heat can give rise to high velocity winds. In the configurations described for the solar nozzle this may give rise to very high “g” forces. If we take the latter model as an example it is believed that incoming air will be accelerated in the nozzle to a velocity of 50 m/s over a distance of 3 metres. From the simple equations of motion

$$v^2 = u^2 + 2as$$

$$\text{acceleration} = \frac{50 \times 50}{2 \times 3} = 400\ \text{m/s}^2 = 40\ \text{g}$$

The convective acceleration at the mouth of the nozzle will only be 10^{-4} of this amount but progressively as air flows towards the throat of the nozzle these lift forces will become progressively stronger. These need to be taken into account in the design of the nozzle and its support (Figure 11).

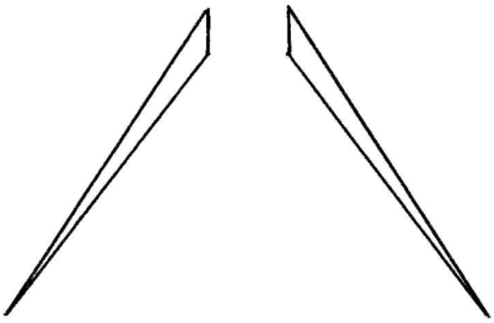

Figure 11

The nozzle will need to be of progressively thicker and stronger material towards the throat. Aerodynamic factors cf turbulence need also to be taken into account in the design of the throat of the nozzle and its exit. The nozzle will have to be anchored securely to the ground and to the remainder of the configuration. The outer shield suggested in the latter models could help provide that structural support.

Conclusions

The ideas presented in this paper are a development of earlier work on this website but with the major departure that the solar nozzle involves an open cycle. They have also drawn heavily on the detailed theoretical work published on the solar chimney.

A prototype solar nozzle is described of 10 metres height, 10 metres base diameter and one metre throat diameter. A multi-layered or honeycomb structured solar absorber is placed in the lower levels of the cone with a gap of one metre between the base of the cone and the ground to allow access of incoming air. It is believed that such a structure will convert solar energy into the kinetic energy of air flow in the throat of the nozzle with high efficiency. This can be harnessed by a wind turbine to give an output of up to 59 kilowatts.

The author requests comments, positive or negative on the fundamental concept and on any part of the above paper. He asks that the proposal be investigated theoretically and experimentally at a university department or energy research institute and that a prototype be built for assessment, research and development.

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