Solar Nozzle Revised – a Laboratory Model

Abstract

A small conical solar chimney is described of height 1 m and collector diameter 2 m. In sunny conditions, warm air in the solar collector creates a buoyancy force which draws air through the configuration. The narrow open top of the conical vessel requires multiplication of air flow velocity. It is calculated that 50% of the solar energy absorbed can be converted into kinetic energy of air flow if the open top has a diameter of 11.48 cm. A turbine sited in the throat of the nozzle could harness this kinetic energy and generate electricity. No experimental work has been carried out. The author asks for further theoretical study of the proposal including by computational flow dynamics and for a laboratory model to be built and tested.

Introduction

In November 2007 the author published a paper titled “The Solar Nozzle” and circulated it to some leading experts in solar energy [1]. To date 72 replies have been received – 22 positive, 12 negative and 38 neutral. Five people volunteered to build a small model – three have reported back but with disappointing results. The paper however remains one of the most frequently visited on this website.

The author considered it time to revisit the proposal, to reconsider and simplify the physics and to focus on devising a Laboratory Model. Consider the configuration shown in Figure 1

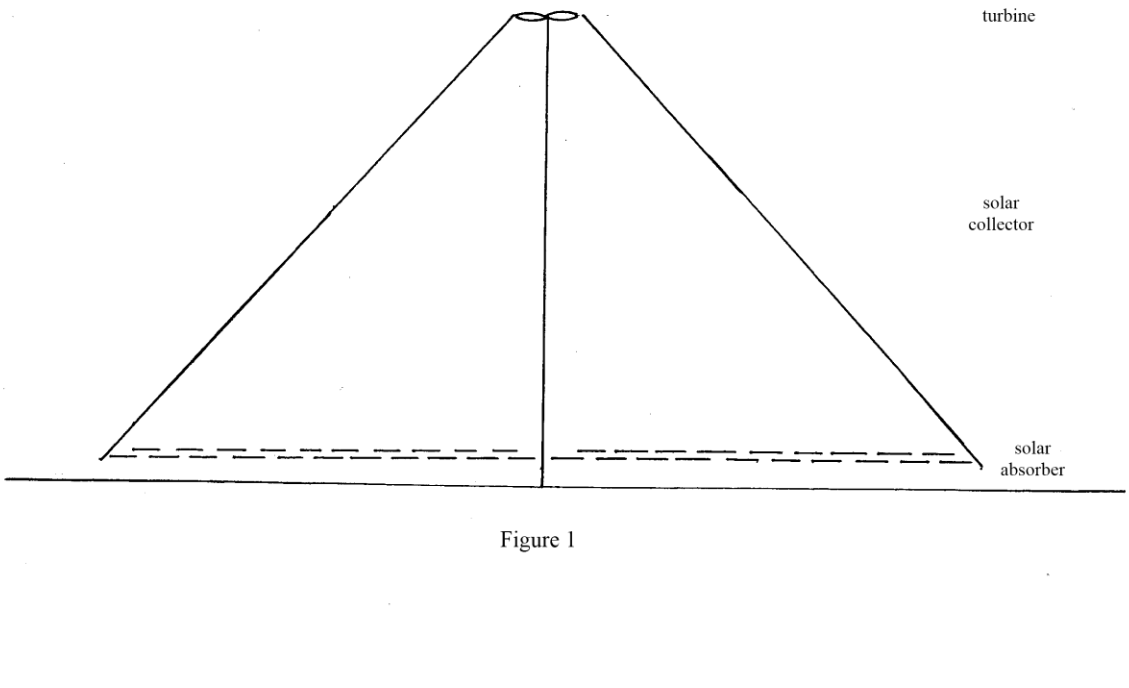

Figure 1

The main structure is a conical solar collector with an open top. The material must be transparent and rigid but preferably not glass because of danger of shatter. It could be of perspex or the transparent polymers used in solar hot water panels.

Inside the cone and above the level of the base of the cone is a multilayered solar absorber. It should be of very open construction with abundant gaps or spaces in the sheeting or lattice structure to allow easy through flow of air. The absorber material is metallic with its upper surface coated with solar absorber paint. Please note again that the solar absorber is NOT at ground level but ABOVE the level of the base of the cone so that all solar energy absorbed must rise through the cone.

A turbine is sited at the open top of the cone with its axle anchored to the ground at the centre of the structure.

Incident solar energy is taken up by the solar absorber warming the air in its immediate neighbourhood. The warm air rises because of its lower density, drawing fresh ambient air from beneath to replace. A convection current is set up with warm air rising from the absorber and travelling through the open top of the cone. As the cross-sectional area narrows the velocity of the air flow increases. A turbine sited as shown can harness this kinetic energy of air flow and generate electricity for export.

Theoretical Development

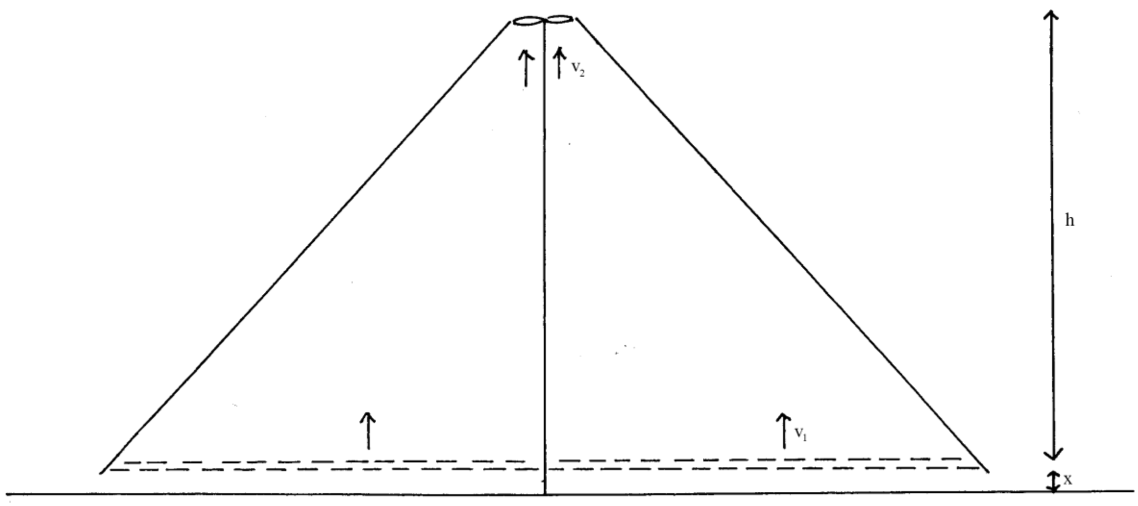

Figure 2

Consider that in Figure 2

h	height of conical solar nozzle
A_1	area of solar absorber
A_2	cross-sectional area of turbine
v_1	velocity of air flow through solar absorber
v_2	velocity of air flow through turbine
T	ambient temperature

ΔT	excess temperature (above ambient) of air in solar collector
$\Delta T'$	fall in temperature of air flow through turbine
x	clearance between ground and base of solar collector
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 physics of the solar nozzle draws from a theoretical understanding of the solar chimney [2]. Consider an open cylindrical chimney of height h containing air at a temperature T + ΔT. The velocity of air flow through the chimney is given by

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

For the solar nozzle, the conical structure has only one third of the volume of warm air compared to the cylindrical chimney and only one third of the buoyancy force. Thus in the configuration shown in Figure 2

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

At constant insolation there will be a steady flow of air through the configuration. Thus

mass flow through solar absorber = mass flow through turbine

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

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

As air flow rises through the solar collector its velocity must increase from v_1 to v_2 because of the reducing cross-sectional area. The extra kinetic energy of the air flow comes from the internal energy of the air whose temperature falls by an amount ΔT′

gain in kinetic energy = mass flow x heat capacity x temperature fall

$$\frac{1}{2} \dot{m} v_2^2 - \frac{1}{2} \dot{m} v_1^2 = \dot{m} C_p \Delta T'$$

where $\dot{m}$ is the mass flow. Consider that $v_2 >> v_1$

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

The energy that is taken up by the solar absorber provides the excess temperature ΔT for buoyancy which creates the air flow and must provide also the kinetic energy for the turbine. The air flow must be raised in temperature by ΔT + ΔT′ as it passes through the solar absorber.

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

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

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

Equations (1) to (4) govern the energy changes taking place as air flows through the solar collector and turbine. In the 4 equations there are 5 constants T, g, C_p, ρ, I and 7 variables h, A_1, A_2, v_1, v_2, ΔT, ΔT′. If 3 of the variables are fixed for a particular model, it is then possible to calculate the other 4 variables.

Laboratory Model

Consider a model of modest dimensions that could be built indoors or outdoors in a sunny position using laboratory facilities. Consider a conical solar collector of height 1 metre and diameter 2 metres.

Consider also that ΔT = ΔT′ so that the configuration devised has overall efficiency of up to 50%. Of the solar energy absorbed 50% will be available as kinetic energy for the turbine and 50% is lost to the system as heat energy in the exit air. This is necessary to provide buoyancy, the air flow leaving the turbine at a temperature T + ΔT.

Thus in equations (1) to (4) consider

h	=	1 m	T	=	300	K
A_1	=	3.14 m^2 (diameter 2m)	g	=	9.81	ms^{-2}
ΔT	=	ΔT′	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
			ρ	=	1.18	$kg\ m^{-3}$
			I	=	750	$w\ m^{-2}$

From equation (1)

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

$$= \frac{2}{3}\frac{\Delta T}{300} \times 9.81 \times 1$$

$$v_1^2 = 0.0218\ \Delta T$$

From equation (4)

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

$$750 = 1.18\ v_1 \times 1005\ (\Delta T + \Delta T)$$

$$v_1 \Delta T = 0.3162$$

Thus

$$v_1^3 = 0.0218 \times 0.3162$$

$$= 0.006894$$

$$v_1 = 0.1903\ ms^{-1}$$

$$\Delta T = 1.661$$

$$\Delta T' = 1.661$$

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

$= 2 \times 1005 \times 1.661$

$v_2 = 57.79\ ms^{-1}$ (120 mph)

From equation (2) $A_1\ v_1 = A_2\ v_2$

$$A_2 = \frac{3.14 \times 0.1903}{57.79}$$

$A_2 = 0.01034\ m^2$

This gives a turbine diameter of 0.1148 m or 11.48 cm.

Thus the laboratory model has ambient air warmed by 3.222K as it passes through the solar absorber. One half of the extra energy is used to provide buoyancy giving an air flow velocity of 0.1903 ms^{-1} at the level of the absorber. The other half of the solar energy absorbed is required to provide kinetic energy – the constriction caused by the narrow neck of the conical vessel requires acceleration of the air flow to 57.79 ms^{-1} (120 mph). This kinetic energy can be harnessed by a turbine and exported as electricity. Exit air leaves the turbine at a temperature 1.661 K above ambient.

Calculation check

At insolation I = 750

total solar energy absorbed = $I\ A_1$

= 750×3.14

= 2355 watts

kinetic energy of air flow through turbine = $\frac{1}{2}\ \rho\ A_2\ v_2^3$

= $\frac{1.18}{2} \times 0.01034 \times (57.79)^3$

= 1177 watts

heat loss in exit air = mass flow x heat capacity x temperature rise

= $\rho\ A_1\ v_1\ Cp\ \Delta T$

= $1.18 \times 3.14 \times 0.1903 \times 1005 \times 1.661$

= 1177 watts

Clearance – value of x

Consider the velocity of air inflow between the ground and the base of the solar collector at its perimeter to be v_x and that the diameter of the collector base is D

volume inflow beneath perimeter of collector	=	volume flow through turbine
$\pi D x v_x$	=	$A_2 v_2$

Consider that it is desirable to have

$$v_x = 0.1 v_2$$

$$x = \frac{A_2}{0.1 \pi D}$$

$$= \frac{0.01034}{0.1 \times 3.14 \times 2}$$

$$x = 0.016 \text{ m}$$

Thus the configuration requires a clearance of 1.6 cm between the base of the collector and the ground.

Turbine specification

The solar nozzle described requires a turbine of axle height 1 m and blade diameter 11.48 cm. When I = 750 air flow velocity is 57.79 ms^{-1} (120 mph) with available kinetic energy of 1177 watts.

Figure 3 gives the dimensions for the laboratory model suggested.

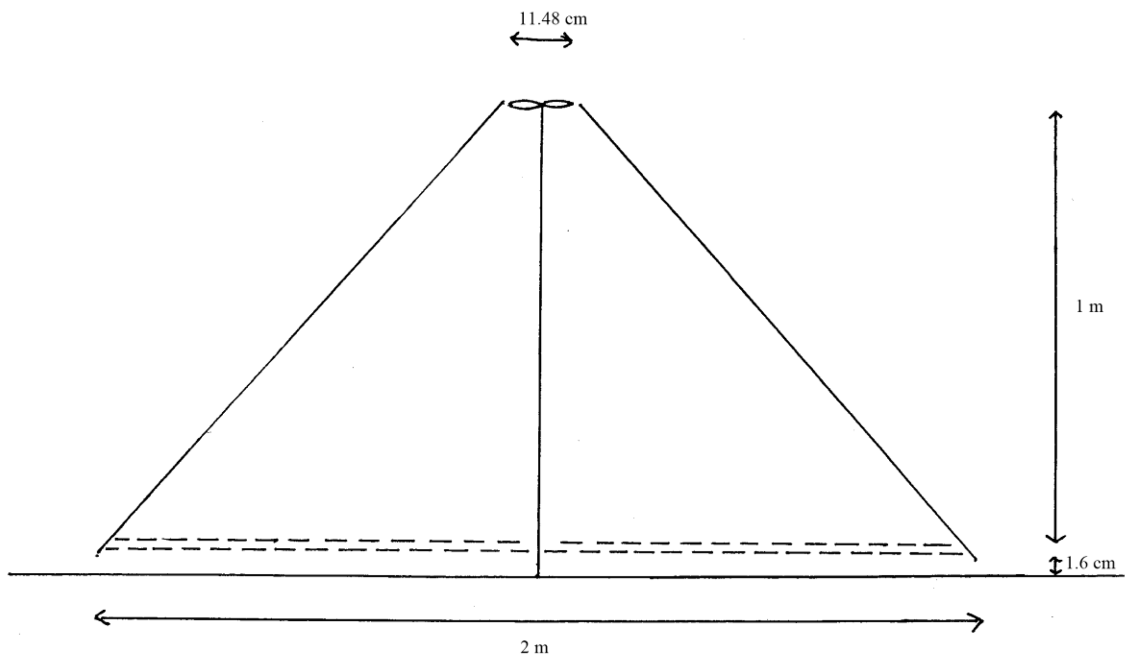

Figure 3

Work outline for research project

The author believes that the proposal outlined in this paper could be the subject of a research project at a university department, energy research institute or solar energy company and suggests:

- The physics should be checked. If there is error, difference of view or challenge to the conclusions, please write to the author.
- The theoretical treatment above considers energy flow only – energy added by the absorber, removed by the turbine and energy loss in exit air. Other parameters could be considered eg density, pressure changes ...
- Computational flow dynamics – the author would be very grateful if there was a study by CFD of the model proposed.
- An experimental model could be built initially with no turbine installed. The conical vessel should be rigid, air tight and built of perspex or transparent polymer. Care should be taken in operation as there is some danger of shatter of the open top of the cone due to the high acceleration, high velocity air flow through the narrow exit. The velocity of the air flow through the open top can be measured using an anemometer. Results should be correlated with insolation, time of day, seasonal fluctuations, ...
- With given solar collector dimensions, it would be interesting to try variations of the cross-sectional area for exit air checking against velocity.
- The geometry of the open top could be varied. As presented it is simply a circular exit but should there be some element of curvature as in a convergent-divergent nozzle and some reinforcement to safeguard against shatter?
- The experimental model only achieves real importance if a turbine is installed as described and electricity generated and exported. A turbine would need to be found and modified or built .. of the dimensions and capacity calculated.

The only precedent to the project suggested above comes from research work by Premkumar and Ramachandran [3] on an earlier proposal, the "buoyancy driven solar engine". CFD study gave "promising" results but experimental investigation using a laboratory model gave "disappointing" results. Nevertheless an air flow velocity of up to 22 ms^{-1} was achieved. Their work provides considerable proof of concept.

Significance of Results

If it was indeed possible to build a laboratory model solar nozzle and achieve efficiency of conversion of solar energy into electricity of anything approaching 50%, then on its own that would be a result of great significance. It could make possible a new approach to harnessing solar energy potentially as important as photovoltaics or concentrated solar power. It could pave the way for larger models to be built of height 2 – 10 – 50 m and collector diameter 5 – 50 – 300 m. The smaller versions could be developed for electricity supply to individual households, businesses or rural villages in developing countries. The larger models could be built in repeat units on desert land for large scale generation of solar electricity.

Conclusion

In this paper a novel variation of the solar chimney is described which has a considerable area solar absorber base and a conical chimney with an open top and of only modest height. Solar energy absorbed creates an up draught of air which must acquire high velocity to flow through the narrow air exit. A turbine can be placed in the throat of the air exit to generate electricity. The author describes a laboratory model and asks that further theoretical work be carried out and that the model be built, tested and developed. If the ideas are correct they could lead to small scale solar electricity generation using natural convection and larger dimension solar nozzles that could be built in repeat patterns for large scale generation.

References

[1] www.globalwarmingsolutions.co.uk November 2007 The Solar Nozzle.

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

[3] M. Premkumar and S. Ramachandran, IEEE Frontiers in Automobile and Mechanical Engineering, 2010, 212-215.

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