The Solar Nozzle – A Research Proposal

Abstract

A theoretical model is described for harnessing solar energy using natural convection. A solar absorber is sited at the base of an empty open-ended conical vessel made of glass or transparent polymer. Convection currents are established that dissipate the heat absorbed. Warm air rises from the absorber drawing ambient air from beneath to replace. As the air rises, the narrowing cross-section of the conical vessel multiplies the vertical air flow velocity. A turbine sited at the top of the open-ended cone can harness the kinetic energy of the air flow generating electricity. A possible laboratory model is described of height 1 m and absorber area 4 m^2 which could generate up to 1.5 kilowatts output. The author asks readers to conduct research work on such an experimental model. If successful the solar nozzle described and/or larger versions could generate electricity for individual homes in advanced countries and for rural villages in developing countries.

Introduction

The smoke jack devised by Leonardo da Vinci (1452–1519) has been quoted in many reviews as the earliest illustration of the principles of the solar chimney. Al-Kayiem and Aja [1] describe the use of "hot rising air in a chimney to drive a windmill which rotates his roasting spit connected to the windmill above a fireplace" as shown in Figure 1.

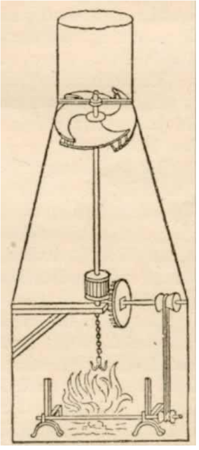

Figure 1

If we look carefully at the smoke jack the key reason why it works is that it includes a venturi or nozzle. In the above sketch the diameter of the combustion section is 2.3 cm whilst the diameter of the windmill is 1.0 cm. This means that the velocity of vertical air flow is multiplied by

$$\left(\frac{2.3}{1.0}\right)^2 = 5.29$$

as it passes through the throat of the venturi. The available kinetic energy for the windmill is multiplied by

$$(5.29)^2 = 28.0$$

If the total structure had been cylindrical, the combustion products would not have had the mechanical energy to drive the windmill. But the venturi multiplies the available kinetic energy 28 fold rotating the roasting spit.

One would have thought that the above principle of using a venturi would have been adopted into solar chimney design. But there is no example of the use of a venturi to multiply air flow velocity in any model solar chimney. The one exception is the conical solar chimney described by Padki and Sherif [2] with the turbine sited at the top of the chimney. They calculated that its efficiency would be

A_i	chimney entrance cross-sectional area
A_e	chimney exit cross-sectional area

$$\left(\frac{A_i}{A_e}\right)^2 \qquad \text{times that of a cylindrical solar chimney.}$$

There is no clear explanation in the literature as to what happened to the promising ideas of the Florida conical solar chimney.

The present author published proposals on this website [3] titled "The Solar Nozzle" (Nov 2007) and "Solar Nozzle Revised" (Nov 2014). There were many favourable replies and limited but unsuccessful experimental work. The author now realises that there were some important mistakes in the physics. The present proposal is a development of the above work.

The Solar Nozzle

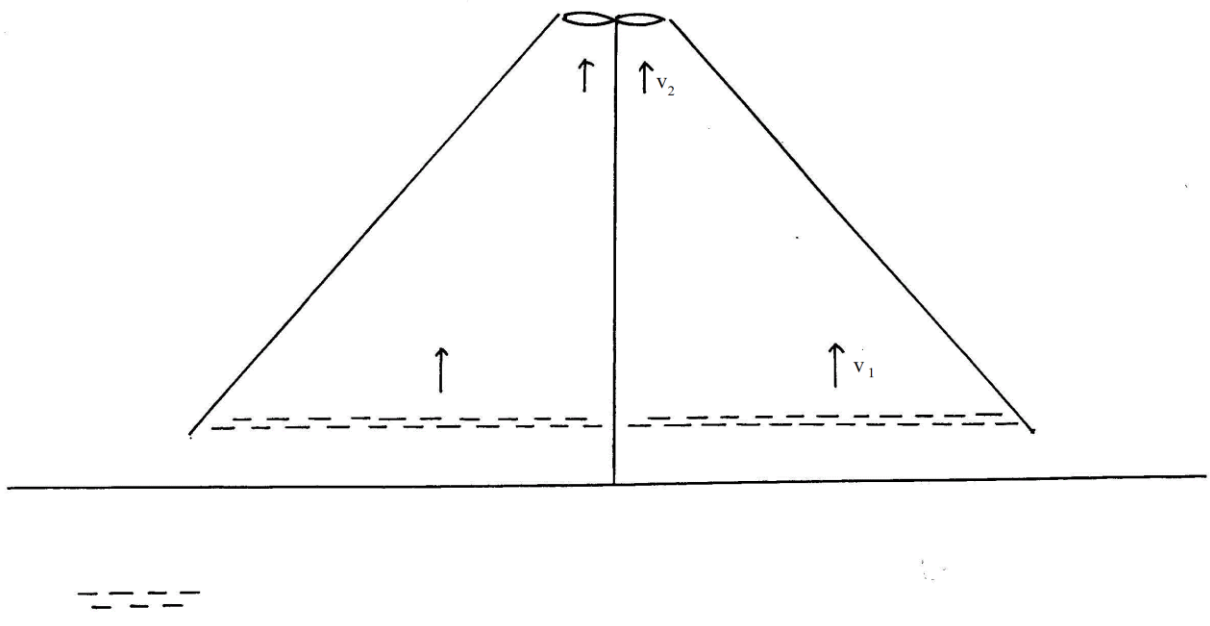

Figure 2

Consider the configuration shown in Fig 2.

The main structure is an open-ended empty cone made of glass or transparent polymer and supported on legs at intervals around the lower circumference. There is a small air gap or clearance between the base of the cone and the ground to allow incoming air flow. The solar absorber is supported above the ground and at a level **above** that of the base of the cone. The solar absorber is a metal coated with absorber paint, of quite open structure to allow easy through flow of air and of 2 or 3 layers so that all incident solar energy is absorbed.

Solar energy taken up by the absorber warms the air in its vicinity which rises because of its lower density drawing fresh air from beneath. As the warm air rises from the absorber, the vertical velocity of the air flow increases as the cross-section of the cone narrows. Flow kinetic energy will be at its maximum at the top of the cone in the throat of the nozzle. A turbine intercepts the air flow generating electricity.

Theoretical Development

Consider that in Figure 2

h	height from solar absorber to turbine
A_1	cross-sectional area solar absorber
A_2	cross-sectional area turbine
v_1	velocity of air flow at level solar absorber
v_2	velocity of air flow through turbine
ΔT	excess temperature (above ambient) exit air post turbine
$\Delta T'$	fall in temperature of air flow through turbine
T	ambient temperature
g	gravitational constant
ρ	density of air at atmospheric pressure and temperature T
C_p	heat capacity of air at constant pressure and temperature T
I	insolation

It is assumed that the turbine is of high efficiency, that exit air leaves the turbine at a temperature $T + \Delta T$ and that $\Delta T'$ is used to provide the kinetic energy of air flow through the turbine.

The velocity v_1 of air drawn through the solar absorber is given by the solar chimney equation [4, 5]

$$v_1^{\,2} = 2\,\frac{\Delta T}{T}\,gh \tag{1}$$

Mass flow through the solar absorber must equal mass flow through the turbine

$$A_1\, v_1\, \rho_1 = A_2\, v_2\, \rho_2$$

Assuming there is little change in density

$$A_1\, v_1 = A_2\, v_2 \tag{2}$$

As rising air accelerates from velocity v_1 to v_2 the increase in flow kinetic energy causes a fall in temperature $\Delta T'$

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

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

when $\dot{m}$ is the mass flow. Now consider that $v_2 >> v_1$ then $v_1{}^2$ can be neglected compared to $v_2{}^2$ and

$$v_2{}^2 \quad = \quad 2\, C_p\, \Delta T' \qquad (3)$$

The solar energy absorbed provides the mass flow through the absorber with an increase in temperature ΔT which provides the buoyancy that drives the air flow. It also provides a further increase ΔT′ to provide the kinetic energy for air flow through the turbine and which is exported as electricity.

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

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

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

Equations (1) – (4) contain 7 variables $h\ A_1\ A_2\ v_1\ v_2\ \Delta T\ \Delta T'$ and 5 constants $T\ g\ \rho\ C_p\ I$. If 3 of the variables are fixed the algebra is soluble.

Laboratory scale solar nozzle

Consider that in Figure 2

$h = 1$ m
$A_1 = 4$ m^2
$\Delta T = \Delta T'$

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

The height is selected for convenience for an indoor setting. The absorber area could be anything from 1-10 m^2 but is selected as 4 m^2 to give a modest energy input for experimental work. It is assumed that ΔT = ΔT′ so that the model solar nozzle devised has an efficiency of 50%. An ambient temperature 300° K is considered to replicate warm climates. The level of insolation assumed is for maximum summer UK.

From equation (1)

$$v_1{}^2 \quad = \quad 2\, \frac{\Delta T}{T}\, gh$$

$$v_1{}^2 \quad = \quad 2\ \frac{\Delta T}{300}\ \text{x}\ 9.81\ \text{x}\ 1$$

$$v_1{}^2 \quad = \quad 0.0654\, \Delta T$$

From equation (4)

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

$$750 \quad = \quad 1.18\ \text{x}\ 1005\, v_1\, (\Delta T + \Delta T)$$

$$v_1\, \Delta T \quad = \quad \frac{750}{1.18\ \text{x}\ 1005\ \text{x}\ 2}$$

$$= \quad 0.3162$$

From (1) and (4)

$$\begin{aligned} v_1^{\,3} &= 0.0654 \times 0.3162 \\ &= 0.02068 \\ v_1 &= 0.2745\ \mathrm{ms}^{-1} \\ \Delta T &= 1.152\ ^{o}\mathrm{K} \end{aligned}$$

From equation (3)

$$\begin{aligned} v_2^{\,2} &= 2\, C_p\, \Delta T' \\ &= 2 \times 1005 \times 1.152 \\ v_2 &= 48.12\ \mathrm{ms}^{-1} \end{aligned}$$

From equation (2)

$$\begin{aligned} A_1\, v_1 &= A_2\, v_2 \\ A_2 &= \frac{4 \times 0.2745}{48.12} \\ &= 0.02282\ \mathrm{m}^2 \end{aligned}$$

This gives a turbine diameter of 0.1705 m

CHECK

maximum insolation $\quad I\, A_1 = 750 \times 4$

$= 3000$ watts

maximum kinetic energy through turbine

$$\begin{aligned} &= \tfrac{1}{2}\, \rho\, A_2\, v_2^{\,3} \\ &= \tfrac{1}{2} \times 1.18 \times 0.02282 \times (48.12)^3 \\ &= 1500 \text{ watts} \end{aligned}$$

heat loss in exit air

$$\begin{aligned} &= \rho\, A_1\, v_1\, C_p\, \Delta T \\ &= 1.18 \times 4 \times 0.2745 \times 1005 \times 1.152 \\ &= 1500 \text{ watts} \end{aligned}$$

Clearance beneath nozzle

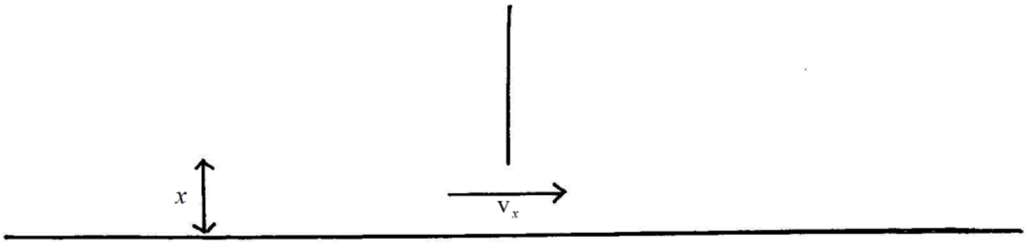

Figure 3

Consider that the base of the perimeter of the solar nozzle (Figure 3) is at a height x above the ground and that incoming air has a velocity v_x

rate of flow of incoming air = rate of outflow through turbine

$$\pi D x v_x = v_2 A_2$$

where D is the diameter of the base. In the above calculation $A_1 = 4 \text{ m}^2$ giving D = 2.257 m. It is suggested that it would be reasonable to have $v_x = 0.1 v_2$

$$x = \frac{v_2 A_2}{\pi D v_x}$$

$$= \frac{0.02282 v_2}{3.14 \times 2.257 \times 0.1 v_2}$$

$$x = 0.03220 \text{ m}$$

Thus there should be a minimum distance of 3.22 cm between the base of the perimeter of the solar nozzle and the ground.

Comment on results of laboratory model

If experimental work were to confirm the above calculations it would be an extraordinary result. It would mean that a small model 1 m high and barely 2 m diameter could generate up to 1.5 kw in bright sunshine. The absorber and conical nozzle are relatively straightforward to design. The most difficult component is the turbine of 0.1705 m diameter to harness air flow velocity of up to 48 ms^{-1}. If the solar nozzle could be developed at a modestly economic price, there is potentially a massive market for individual households worldwide.

The Solar Nozzle – Larger Models

If the laboratory model described gave successful results larger models could be developed where economies of scale should apply. Table 1 has been compiled using exactly parallel calculations to those outlined above.

The heights considered for the nozzle are 1, 2, 5, 10 and 20 m with the area of the solar absorber/collector increasing in step. In each case it has been assumed that $\Delta T = \Delta T'$ so that each configuration is designed for 50% efficiency.

height h	1	2	5	10	20	m
area absorber A_1	4	12	25	100	400	m^2
$\Delta T = \Delta T'$	1.152	0.9143	0.6737	0.5347	0.4244	K
v_1	0.2745	0.3458	0.4694	0.5914	0.7451	ms^{-1}
v_2	48.12	42.87	36.80	32.78	29.21	ms^{-1}
A_2	0.02282	0.09680	0.3189	1.804	10.20	m^2
turbine diameter	0.1705	0.3511	0.6374	1.516	3.605	m
maximum output	1.500	4.500	9.375	37.5	150	kw
clearance *x*	0.032	0.079	0.180	0.48	1.439	m

Table 1

Solar nozzles with h = 1-2 and A_1 = 4-20 could be developed for garden solar electricity in individual households in advanced countries and for groups of houses in rural developing countries. Solar nozzles with h = 5-20 could produce enough electricity for large villages. Note that the value of the clearance *x* increases disproportionately with greater height. The extra height between the ground and the absorber could easily accommodate considerable energy storage capacity using water tubes [6] to allow daytime solar to provide evening and night generation.

Shape of the Nozzle

This paper has assumed that the solar nozzle would have the open-ended conical shape (1) below but other designs are possible (Figure 4)

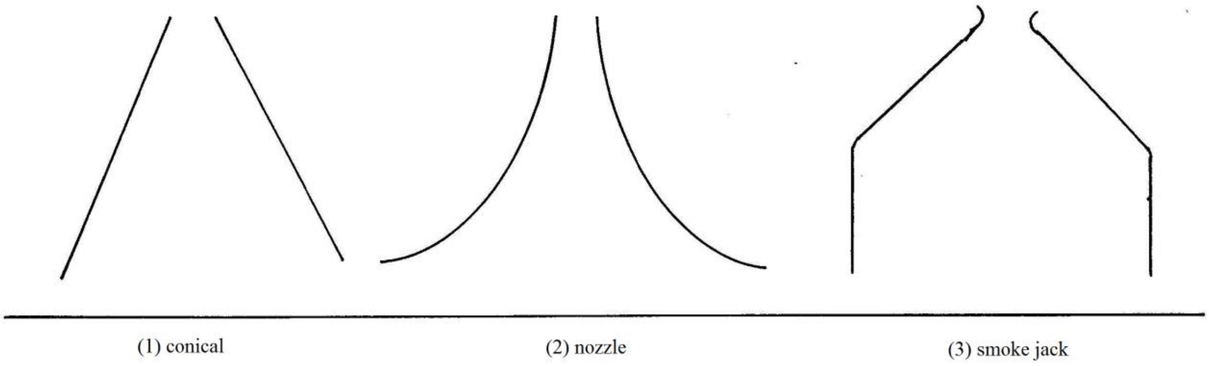

Figure 4

The conical shape (1) is the simplest and easiest to build but there could be problems of structural stress in the neck of the cone as air flow is accelerated to high velocity. The nozzle shape (2) is almost horizontal at its lower level but rises smoothly to the vertical as air flow strikes the turbine. The air flow converges gently and gradually, the configuration being designed to reduce stresses caused by acceleration. The smoke jack shape (3) allows vertical velocity above the absorber to be well established prior to acceleration through the throat. Calculations will be the same for all three depending only on the height from the absorber to the turbine and unaffected by the volume of the vessel. The author's preference is (2) > (3) > (1) for reasons of strength and resilience but the conical shape (1) will be easier and cheaper to build.

Safety

If the solar nozzle is made of glass there must be a danger of shattering around the neck of the vessel. Perspex or other transparent plastic could be alternatives or perhaps a protective metal jacket could be fitted over the upper reaches of the vessel.

Research suggestions

The author has no laboratory and has conducted no experimental work on this proposal. He asks research workers with a background in the solar chimney to consider the enclosed and possible work to validate/disprove/further the ideas. Any comments are welcome particularly any challenge/correction/development of the physics presented. If it is your view that there is a fundamental error/wrong assumption/mistake in the calculations – please write. Similarly, any theoretical studies or experimental work could be instructive e.g. to build a nozzle initially with no turbine and measure temperature changes and especially air velocity through the throat of the cone. One could start perhaps with a wide open end and gradually narrow to confirm whether there is the expected multiplication of air flow velocity. Then install a turbine – there is a problem of course in that it would need to be designed and built for the particular nozzle. But the results could be quite outstanding.

Conclusion

If the above proposal was shown to work experimentally it would undermine/demolish the second law of thermodynamics. Most physicists interpret the second law as meaning that there is a maximum efficiency of $\Delta T/T$ for the conversion of heat into mechanical energy. The author believes that this is wrong – and that an efficiency of 50% plus is possible using the model and principles outlined.

If an efficient working model could be developed of height 1-3 m there is potentially a very large market in the gardens of individual homes in advanced countries cf roof photovoltaics but with the advantage of energy storage. Solar nozzles of height 5-10 m could provide village solar electricity to meet the enormous potential demand in rural areas of developing countries. It could provide solar electricity at ambient temperature with no water demand and with storage for night generation.

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