Convergent Solar Chimney – an outline for an Experimental Model

Abstract

A convergent solar chimney requires that the velocity of air flow at the top of the chimney is many times that at the base of the chimney. The multiple is the ratio of the area of the base of the chimney to the area of the top of the chimney. Available kinetic energy for a turbine sited at the top of the chimney is multiplied by the square of this ratio. It should thus be possible to design a convergent solar chimney of modest height but with high efficiency.

Calculations have been carried out on models of height 3, 5, 10 and 20m using high area ratios. In this way an efficiency of about 50% could be achievable.

Introduction

The principles of the solar chimney have been elaborated in detail by Schlaich et al. [1, 2]. Hundreds of papers have been published on the tall cylindrical structure and there have been many excellent reviews eg [3, 4].

Proposals for a radically different conical solar chimney were developed by Sherif et al. in 1998-9 [5-7]. Air flow velocity is multiplied as it rises through the narrowing cross-section so that a turbine sited at the top of the chimney should have much higher efficiency. There were several promising papers. There is no explanation in the literature as to why work on the 'Florida' solar chimney was apparently abandoned.

The present author has developed proposals for a small conical solar chimney and written several papers on this website [8-10]. The particular advantage is that air flow velocity at the base of the chimney is multiplied as it rises to the top of the chimney by the ratio of the area of the base of the chimney to the area of the top of the chimney. Available kinetic energy for a turbine is multiplied by the square of this ratio so high efficiency should be possible with a modest chimney height.

Model Outline

Consider the model shown in Figure 1. The main structure is an open conical configuration made of glass or rigid transparent plastic eg perspex with its weight supported on 4-8 legs sited symmetrically around the circumference of the base. There is a modest gap between the base and the ground to allow air entry.

The solar absorber is sited just above the base of the configuration. This is a metal coated with solar absorber paint that absorbs incident solar energy with high efficiency. It is suggested that there should be two layers of solar absorber with a large proportion of large holes in each layer to allow easy through flow of air but devised such that all incident solar energy is absorbed.

A turbine is sited at the top of the chimney supported by a central axis. The turbine rotates in the horizontal plane absorbing the kinetic energy of rising air flow and exporting it as electricity.

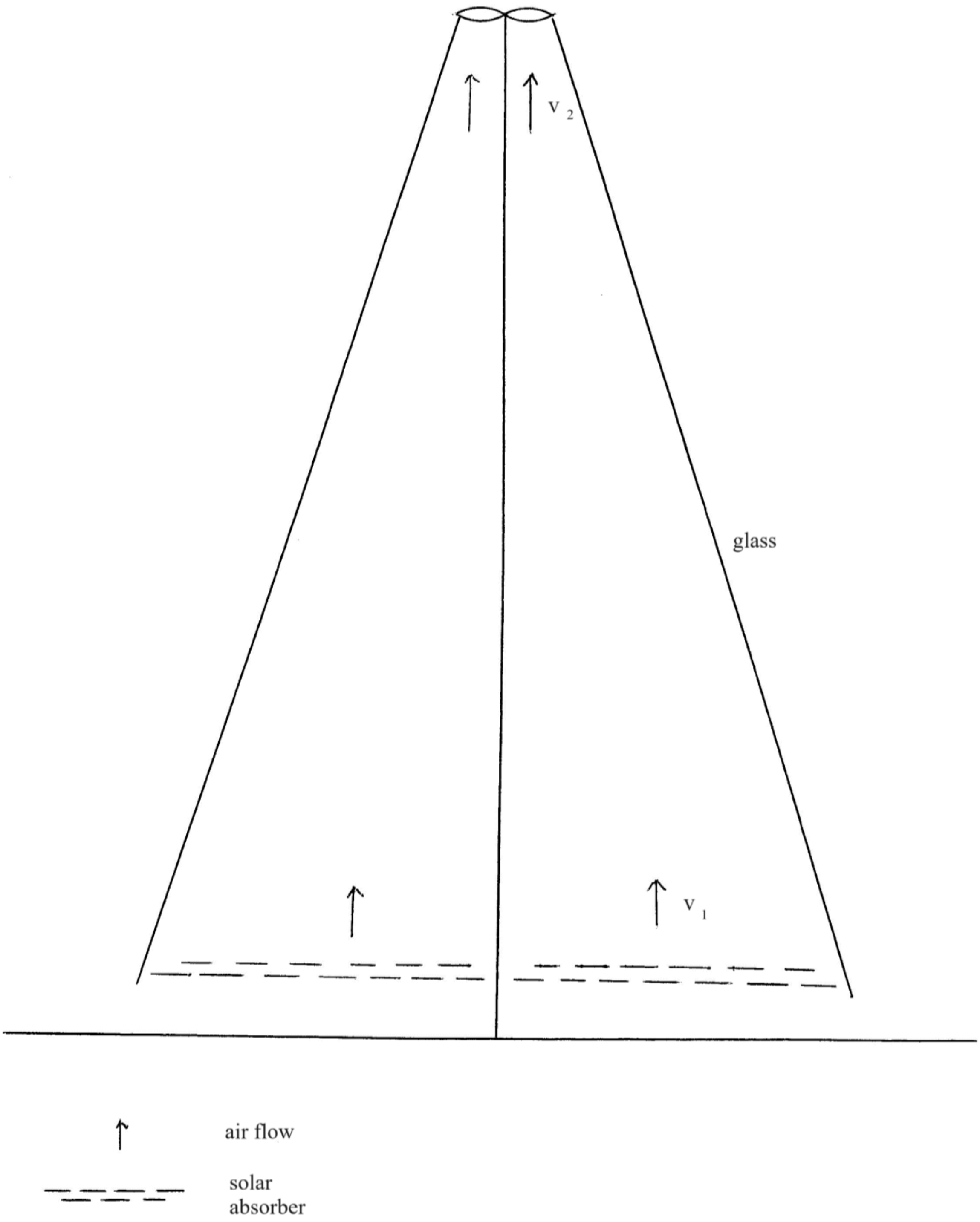

Figure 1

The solar absorber takes up solar energy with high efficiency warming its metallic base and surrounding air. The warmed air rises because it is lighter drawing ambient air from beneath to replace. A convection current is established where the rising air has to gain velocity because of the narrowing cross-section. Some of its internal energy is converted into the kinetic energy of air flow. A turbine sited at the top of the chimney absorbs this kinetic energy generating electricity.

Theoretical Development

Consider that in Figure 1

h	height from solar absorber to top of chimney
A_1	area of solar absorber
A_2	area cross-section of turbine
v_1	velocity of air flow above solar absorber
v_2	velocity of air flow through turbine
T	ambient temperature
ΔT	excess temperature (above ambient) of air flow through chimney
$\Delta T'$	fall in temperature of air flow through turbine
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

The velocity of air flow at the level of the solar absorber is given by the solar chimney equation [1, 2]

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

Constant air flow requires that

air flow through solar absorber = air flow through turbine

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

As air flows through the turbine it surrenders its kinetic energy causing a fall in temperature $\Delta T'$

loss of kinetic energy = mass flow x heat capacity x fall in temperature

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

where $\dot{m}$ is the mass flow

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

As air flows through the solar absorber, it must gain temperature by an amount ΔT that provides buoyancy for air in the chimney and by an amount $\Delta T'$ to compensate for the loss in the turbine

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) – (4) describe all the energy changes taking place in the configuration. They contain 7 variables h A_1 A_2 v_1 v_2 ΔT $\Delta T'$ and 5 constants T g ρ C_p I. If 3 of the variables are fixed the algebra is soluble to calculate the other variables. In this way models can be devised and calculations used to assess their practicality.

Experimental Model

Consider that in Figure 1 the height is 10m, the diameter of the solar absorber 7m and turbine diameter 1m. The insolation considered represents summer UK maximum.

h	=	10 m		T	=	300	°K
A_1	=	38.47 m^2		g	=	9.81	ms^{-2}
A_2	=	0.785 m^2		ρ	=	1.18	$kg\ m^{-3}$
				C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

From equation (1)

$$v_1^{\ 2} = \frac{2\ \Delta T}{300} \times 9.81 \times 10$$

$$v_1^{\ 2} = 0.654\ \Delta T \qquad (1)$$

From equation (2)

$$38.47\ v_1 = 0.785\ v_2$$

$$v_2 = 49\ v_1 \qquad (2)$$

From equation (3)

$$v_2^{\ 2} = 2010\ \Delta T' \qquad (3)$$

From equation (4)

$$750 = 1.18 \times 1005\ v_1\ (\Delta T + \Delta T')$$

Using equations (1) (2) and (3)

$$750 = 1185.9\ v_1 \left(\frac{v_1^{\ 2}}{0.654} + \frac{2401}{2010}\ v_1^{\ 2} \right)$$

$$v_1^{\ 3}\ (2010 + 1570) = 0.6324 \times 0.654 \times 2010$$

$$v_1^{\ 3} = 0.2322$$

$$v_1 = 0.6146\ ms^{-1}$$

From (2) $\quad v_2 = 30.12\ ms^{-1}$

From (1) $\quad \Delta T = 0.5777\ °K$

From (3) $\quad \Delta T' = 0.4513\ °K$

Maximum kinetic energy $= \frac{1}{2}\ \rho\ A_2\ v_2^{\ 3}$

$= 0.59\ (0.785)\ (30.12)^{3}$

$= 12.65$ kw

maximum insolation	=	IA_1
	=	750 x 38.47
	=	28.85 kw
Efficiency	=	$\frac{12.65}{28.85}$
	=	43.86 %

Calculation indicates that at insolation 750 wm^{-2} the velocity of air flow through the turbine is 30.12 ms^{-1} and the kinetic energy 12.65 kw. The conversion of solar energy into available kinetic energy has an efficiency of 43.86%.

If such a model was built in a region with insolation 6 $kwh/m^2/day$ it would generate up to 100 kwh/day.

Calculations have been carried out for models of height 3, 5, 10 and 20m and are presented in Table 1. The parameters for chimney height and the diameter of the solar absorber and turbine have been designed to deliver an efficiency of 40-50% using the 'formula for good efficiency' described later. The larger is the height of the chimney the lower is the area ratio A_1/A_2 required for good efficiency.

Table 1 Results calculated for range of models

chimney height h	m	3	5	10	20
turbine diameter	m	0.2	0.5	1	2
absorber diameter	m	2	4	7	12
slenderness ratio		15	10	10	10
absorber area A_1	m^2	3.14	12.56	38.47	113.0
turbine area A_2	m^2	0.0314	0.1963	0.7850	3.14
area ratio A_1/A_2		100	64	49	36
$h(A_1/A_2)^2$		30,000	20,480	24,010	25,920
x	m	0.04	0.10	0.22	0.46
v_1	ms^{-1}	0.3975	0.4988	0.6146	0.7656
v_2	ms^{-1}	39.75	31.92	30.12	27.56
ΔT	°K	0.8052	0.7609	0.5777	0.4481
$\Delta T'$	°K	0.7860	0.5070	0.4513	0.3779
KE max	kw	1.163	3.767	12.65	38.79
efficiency	%	49.40	39.99	43.86	45.75

Results in the Table show that the value of v_1 rises with the height of the chimney but the value of v_2 falls the taller is the chimney. The values of ΔT and $\Delta T'$ are under 1°C and fall with increasing height of chimney. The smallest chimney with height 3m delivers a maximum 1.163 kw output. The largest model considered with height 20m has a maximum output of 38.79 kw. If built in a warm climate with insolation 6 kwh/m^2/day this would yield an average daily output of 300 kwh.

Further Comments

- Slenderness Ratio Guo et al. [4] draw attention to the importance of the chimney slenderness ratio (SR) which is the ratio of the chimney height to its diameter to maintain good flow in a solar chimney. They suggest an optimum SR of 6-8. The models above have SR 10 or over.

- Value of *x* This is the minimum height of the gap between the ground and the base of the convergent chimney required to allow incoming air flow. This has been calculated to give a maximum velocity of incoming air flow of 5 ms^{-1}.

- Energy Losses There will be some loss through the glass of the convergent chimney but this should be quite small as ΔT and $\Delta T'$ are both below 1°C. There will be considerable energy loss in the turbine though ducted or shrouded turbines are claimed to have an efficiency of 80%. The other major loss is ΔT which is lost as work done against gravity by air rising through the height of the chimney. This is unavoidable as it is the origin of the buoyancy that drives convection.

- A formula for good efficiency Schlaich et al. [1, 2] find that the efficiency of a solar chimney is given by

$$\eta = \frac{gh}{C_p T}$$

  Thus to achieve 100% efficiency with a cylindrical solar chimney would require a height of

$$\frac{1005 \times 300}{9.81} \sim 30{,}000\text{m}$$

  This is in line with the prediction that a 1000m height solar chimney will have a maximum efficiency of about 3% [1, 2].

  In the convergent solar chimney described the velocity of air flow through the turbine is multiplied by A_1/A_2 and efficiency by $(A_1/A_2)^2$. Thus to achieve high efficiency with the present model requires

$$h\left(\frac{A_1}{A_2}\right)^2 \sim 30{,}000$$

  This formula has been used as a guideline to help devise values of h A_1 and A_2 that will give good efficiency.

- Higher Efficiency Parameters for the height of the chimney and the diameter of the solar absorber and turbine have been devised to give a good slenderness ratio and an overall efficiency of 40-50%. In any given configuration, higher efficiency can be achieved by reducing the diameter of the top of the chimney. This will increase the velocity of air flow through the turbine and hence the output and efficiency to perhaps 60-80%. But higher efficiency will be limited by the efficiency of the turbine.

- The author has conducted no experimental work to validate these proposals – the ideas are purely theoretical. Readers are asked to build experimental models to assess and develop the configurations suggested. The smaller models of height 3 and 5m could be developed for individual households. The larger models of height 10 and 20m could generate enough electricity for several households or a small village.

- Larger models can be devised with height 50-100m and proportionally larger solar absorber area and output. There is the practical problem of design and operation of a turbine at a height of 50 or 100m but this is no different in principle to the challenge of wind turbines. Indeed compared to wind turbines, the convergent solar chimney could offer higher efficiency, the greater availability of solar energy and much easier site selection.

Conclusion

Detailed calculations are presented for a convergent solar chimney of height 10m, base diameter 7m and top of chimney diameter 1m. They suggest air flow velocity of 30.12 ms^{-1} at the top of the chimney at insolation 750 wm^{-2} and an efficiency of conversion of solar energy into available kinetic energy of 43.86%. If built in a warm climate this could mean output of 100 kwh/day.

Calculations have been carried out for models of height 3, 5, 10 and 20m. Larger models of height 50 -100m are also possible that would have major advantages over wind turbines. No practical work has been conducted. Readers are asked to consider construction of an experimental model to test and develop the proposals.

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