Multichannel Solar Chimney – dimensions for a demonstration model

Abstract

A rectangular solar chimney of height 5m and cross-section 5 x 1m is described comprising 20 flow channels 0.5m square. This receives warm air from a solar collector of dimensions 5 x 1m and 1m height, which in turn draws ambient air through a nozzle and turbine. By careful selection of the turbine diameter (0.3m) calculation indicates an air flow velocity through the turbine of up to 34 ms^{-1} and conversion of solar energy into mechanical energy with an efficiency over 40%.

Introduction

The solar chimney devised by Schlaich et al. [1] has a large area solar collector (up to 20 km^2), a tall chimney (up to 1000m) and turbines sited around the base of the chimney to harness the kinetic energy of air flow. The output expected is about 200MW with an efficiency of 2–3%.

The present author suggests that to achieve high efficiency and a lower height chimney, the air flow needs to pass through a venturi designed to produce high velocity. The turbine is then sited in the throat of the venturi. The chimney generates a certain velocity of air flow because of the buoyancy of the air column in the chimney. This is multiplied by A_1/A_2 when the air flow passes through a venturi where A_1 is the cross-sectional area of the chimney and A_2 the cross-sectional area of the turbine. Available kinetic energy and efficiency are multiplied by $(A_1/A_2)^2$.

In the ideal configuration A_1 should be as large as possible whilst A_2 is carefully designed to give optimal high velocity. There is a problem however if A_1 is very large. Guo et al. [2] draw attention to the importance of "slenderness ratio" in the design of a solar chimney. This is the ratio of the height of the chimney to its diameter. They suggest that a slenderness ratio (SR) of 6-8 is needed for good flow. This imposes a serious constraint on the diameter of the chimney and A_1.

Multichannel Solar Chimney

The present author suggests that a novel way of achieving high cross-sectional area for the chimney whilst maintaining a good slenderness ratio would be to partition the flow into 10-100 flow channels. Each flow channel would be designed for the height of the chimney, be parallel, discrete and independently have SR greater than the 6-8 recommended. The proposal is outlined in Figure 1.

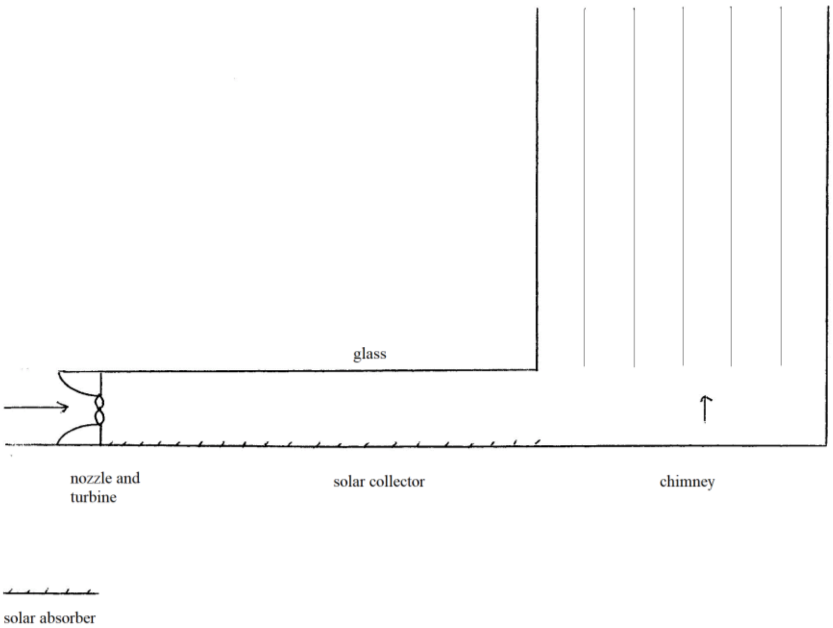

Figure 1

A rectangular configuration is suggested for the solar collector and chimney for ease of construction and to allow multiple units to be built in parallel in an eventual commercial design.

Solar energy is taken up by the absorber warming air in its vicinity which rises. A convection current is established with warm air rising through the chimney drawing ambient air to replace through the nozzle and turbine. By suitably devising dimensions, the velocity of the air flow through the turbine can be many times the velocity of the air flow through the chimney. The kinetic energy of the air flow through the turbine can be harnessed producing electricity.

Danger of Reverse Flow

There is a danger that if the throat of the nozzle is too narrow in Figure 1, that as warm air flows through some of the flow channels, replacement air is drawn through some of the other flow channels in a reverse flow! It is suggested that the solar absorber be sited at the level of the bottom of the turbine and that a wall/solid barrier is built across the solar collector to this level as air enters the chimney, to prevent reverse flow (see Figure 2).

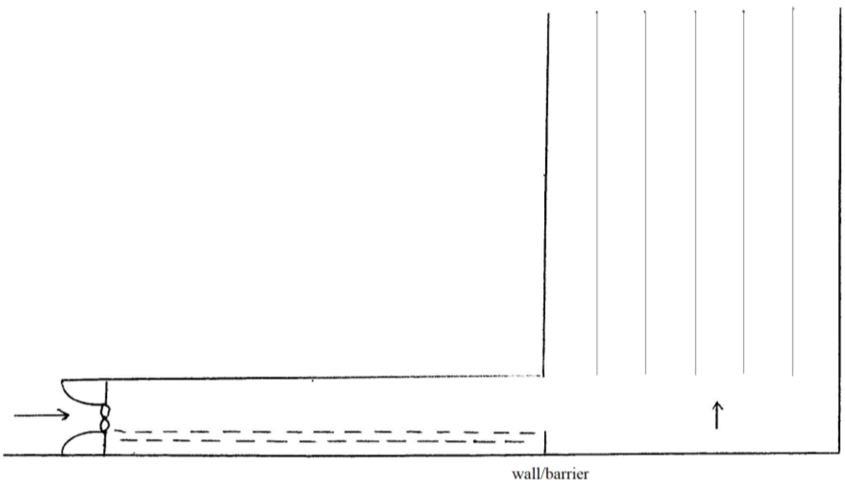

Figure 2

It is also suggested that the solar absorber should comprise two or more layers with intermittent open areas to allow smooth vertical flow and efficient heat transfer from the absorber to the air flow.

Convergent Nozzle

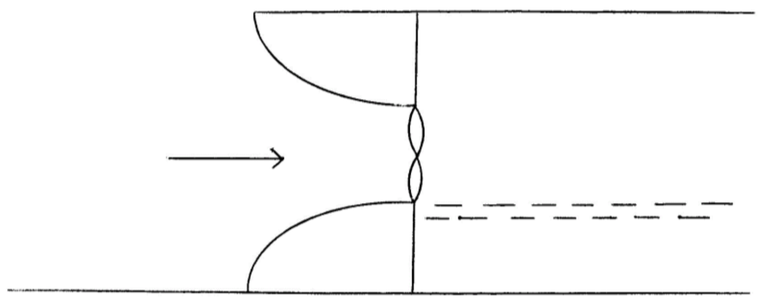

Figure 3

A convergent nozzle is essentially a pipe whose cross-sectional area decreases in the direction of flow (see Figure 3). Air flow is smoothly converted to high velocity. It allows conversion of thermal energy into linear kinetic energy with high efficiency.

Theoretical Development

Consider that in Figure 4

h	height of chimney
A_1	area cross-section of chimney
A_2	area cross-section of turbine
A_3	area solar absorber
v_1	velocity of air flow through chimney
v_2	velocity of air flow through turbine
T	ambient temperature
ΔT	excess temperature (above ambient) of exit air
$\Delta T'$	fall in temperature as air flows 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

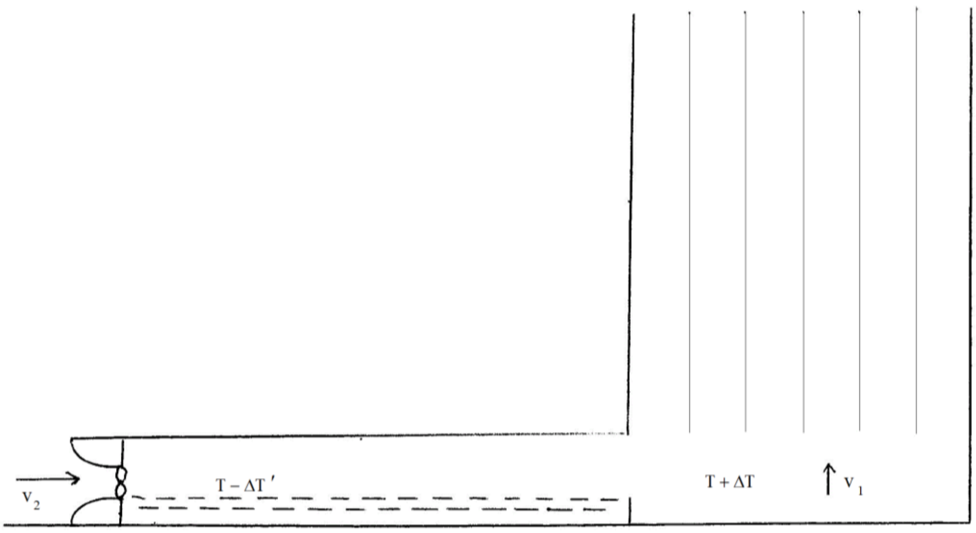

Figure 4

The velocity of air through the chimney is given by the solar chimney equation [1]

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

Assuming little change in density, constant mass flow requires that

volume flow rate through chimney = volume flow rate through turbine

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

As incoming air is accelerated through the convergent nozzle the gain in flow kinetic energy is at the expense of internal energy and causes a fall in temperature $\Delta T'$

gain in 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. It is assumed that the turbine takes up ALL of this kinetic energy.

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

As incoming air flows through the solar collector, solar energy taken up by the absorber raises the temperature of the air flow from $\Delta T'$ below ambient to ΔT above ambient.

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

$$I\,A_3 = \rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T') \qquad (4)$$

Equations (1) – (4) define the energy changes taking place in the configuration. They contain 8 variables h A_1 A_2 A_3 v_1 v_2 ΔT $\Delta T'$ and 5 constants T g ρ C_p I. If 4 of the variables are fixed to define the configuration, algebra allows calculation of the other four. Thus any number of possible dimensions can be investigated.

A formula for good efficiency

In an earlier paper [3] the author has derived a guideline formula for good efficiency

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

where h A_1 A_2 are as defined above. This formula has been used to devise the dimensions below and gives a target efficiency of about 50%.

Dimensions for a demonstration model

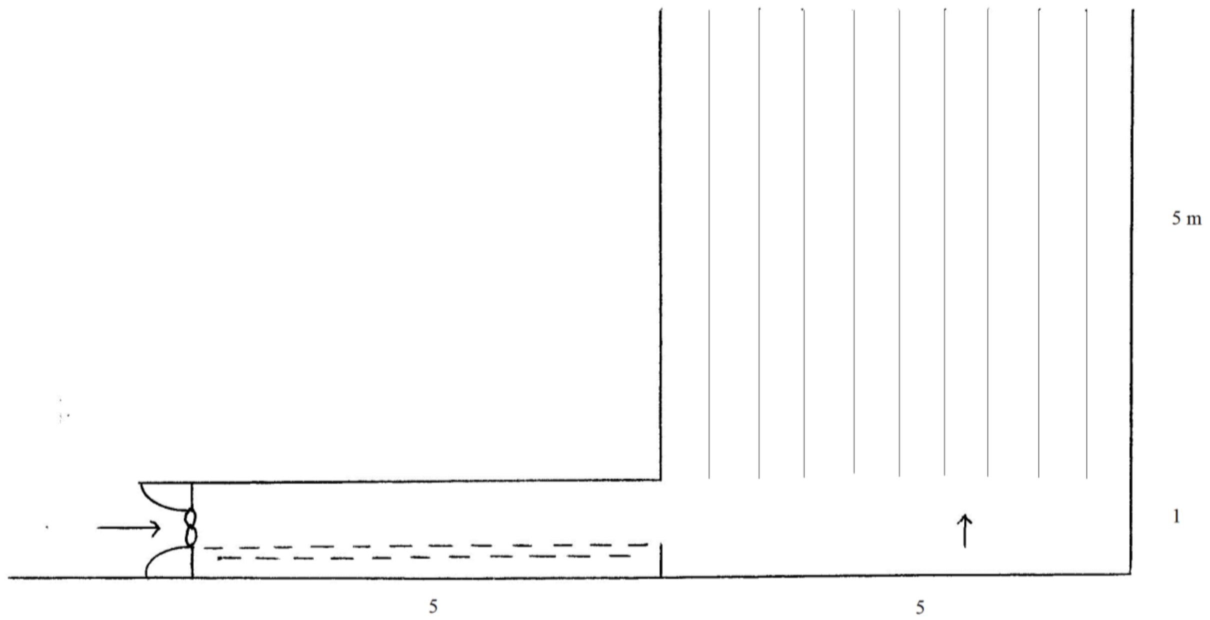

Figure 5

Consider the rectangular configuration outlined in Figure 5. The chimney has height 5m, length 5m and width 1m and is partitioned into 20 parallel flow channels of height 5, length 0.5 and width 0.5m. This gives a chimney cross-sectional area $A_1 = 5\text{m}^2$ and a slenderness ratio of 10 for the flow channels.

Consider that the solar collector has height 1m, that the diameter of the mouth of the nozzle is 1m and that a turbine of diameter 0.3m is sited at the throat of the nozzle

$$A_2 = 3.14\,(0.15)^2$$

$$= 0.07065\ \text{m}^2$$

In this configuration $\frac{A_1}{A_2} = 70.77$ and $h\left(\frac{A_1}{A_2}\right)^2 = 25,040$

indicating an efficiency of 40 - 50%.

Consider the solar collector to be of length 5m width 1m giving $A_3 = 5m^2$. Thus for equations (1) to (4)

h	=	5	m	T	=	300	°K
A_1	=	5	m^2	g	=	9.81	ms^{-2}
A_2	=	0.07065	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	5	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

We can now use equations (1) to (4) to calculate v_1 v_2 ΔT $\Delta T'$

(1)

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

$$v_1^{\,2} = 2\frac{\Delta T}{300} \times 9.81 \times 5$$

$$v_1^{\,2} = 0.327\,\Delta T$$

(2)

$$A_1v_1 = A_2v_2$$

$$5\,v_1 = 0.07065\,v_2$$

$$v_2 = 70.77\,v_1$$

(3)

$$v_2^{\,2} = 2\,C_p\,\Delta T'$$

$$v_2^{\,2} = 2 \times 1005\,\Delta T'$$

$$v_2^{\,2} = 2010\,\Delta T'$$

(4)

$$I\,A_3 = \rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T')$$

$$750 \times 5 = 1.18 \times 5 \times 1005\,v_1\,(\Delta T + \Delta T')$$

$$v_1\,(\Delta T + \Delta T') = 0.6324$$

From (1) (2) and (3) above

$$v_1 \left(\frac{v_1^{\,2}}{0.327} + \frac{5009}{2010} \; v_1^{\,2} \right) \quad = \quad 0.6324$$

$$v_1^{\,3} \; (2010 \; + \; 1638) \quad = \quad 0.6324 \; \text{x} \; 0.327 \; \text{x} \; 2010$$

$$v_1^{\,3} \quad = \quad 0.1140$$

$$v_1 \quad = \quad 0.4848 \;\; ms^{-1}$$

From (2) $\quad v_2 \quad = \quad 34.31 \quad ms^{-1}$

From (1) $\quad \Delta T \quad = \quad 0.7188 \;\; °K$

From (3) $\quad \Delta T' \quad = \quad 0.5857 \;\; °K$

Calculation shows that at insolation 750 wm^{-2} (maximum UK summer) the velocity of air flow through the turbine is 34.31 ms^{-1}, just within the range of commercial wind turbines. The values of ΔT and $\Delta T'$ are both less than 1°K.

For the configuration, maximum insolation

$$I \; A_3 \quad = \quad 750 \;\; \text{x} \;\; 5$$

$$= \quad 3.750 \text{ KW}$$

The maximum kinetic energy available is

$$\tfrac{1}{2} \rho \, A_2 \, v_2^{\,3} \quad = \quad \frac{1.18}{2} \;\; \text{x} \;\; (0.07065) \, (34.31)^{\,3}$$

$$= \quad 1.684 \text{ KW}$$

giving an efficiency of 44.90%.

Additional Comments

- In the model elaborated the area of the collector is the same as the cross-sectional area of the chimney. A larger area solar absorber could be used giving higher ΔT $\Delta T'$ v_1 v_2 and greater output but with the same efficiency.
- The demonstration model suggested has external dimensions of length 11m width 1m height 1m for the solar collector and overall height 6m for the chimney. As it is rectangular, multiple units could be built in parallel.
- Larger models can be devised with chimney height 10-100m and proportionately larger area turbine, solar collector and output. These will be the subject of a future paper.
- Research work published by Premkumar and Ramachandran [4] on the ‘Buoyancy Driven Solar Engine’ provides some proof of concept. This is a simpler configuration but involves similar principles. Their experimental model achieved an air flow velocity of up to 22 ms^{-1}.

Conclusion

A multichannel solar chimney is described of rectangular design comprising dozens of parallel, discrete flow channels. This may allow a chimney of modest height to have a large cross-sectional area and yet retain a good slenderness ratio necessary for good flow. With a turbine generating electricity from incoming air, a demonstration model is described that is calculated to give maximum air flow velocity 34 ms^{-1} and efficiency of over 40%. The author asks experts on the solar chimney to consider the proposal, to carry out a theoretical assessment and to build an experimental model. If the proposal gives successful results, the design is amenable to construction of multiple units in parallel. It could also be scaled up using larger chimney, collector and turbine dimensions to give much higher output at good efficiency.

References

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[3] www.globalwarmingsolutions.co.uk Solar Driven Wind Turbines – an alternative configuration for the solar chimney of modest height and high efficiency. January 2020.

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

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